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Carbon Sequestration Project Portfolio FY2002

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Carbon Sequestration Project Portfolio

Carbon Sequestration Overview

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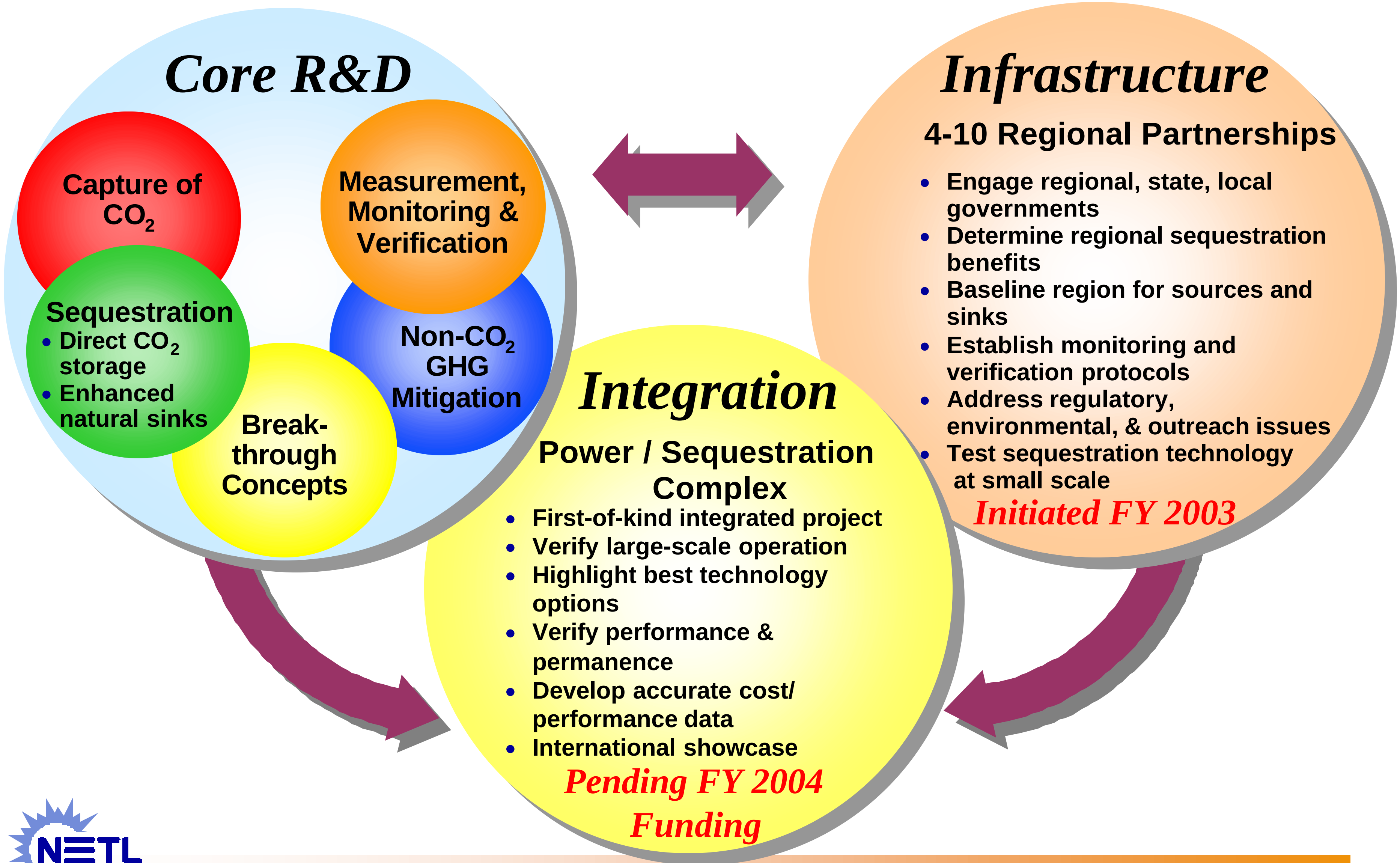
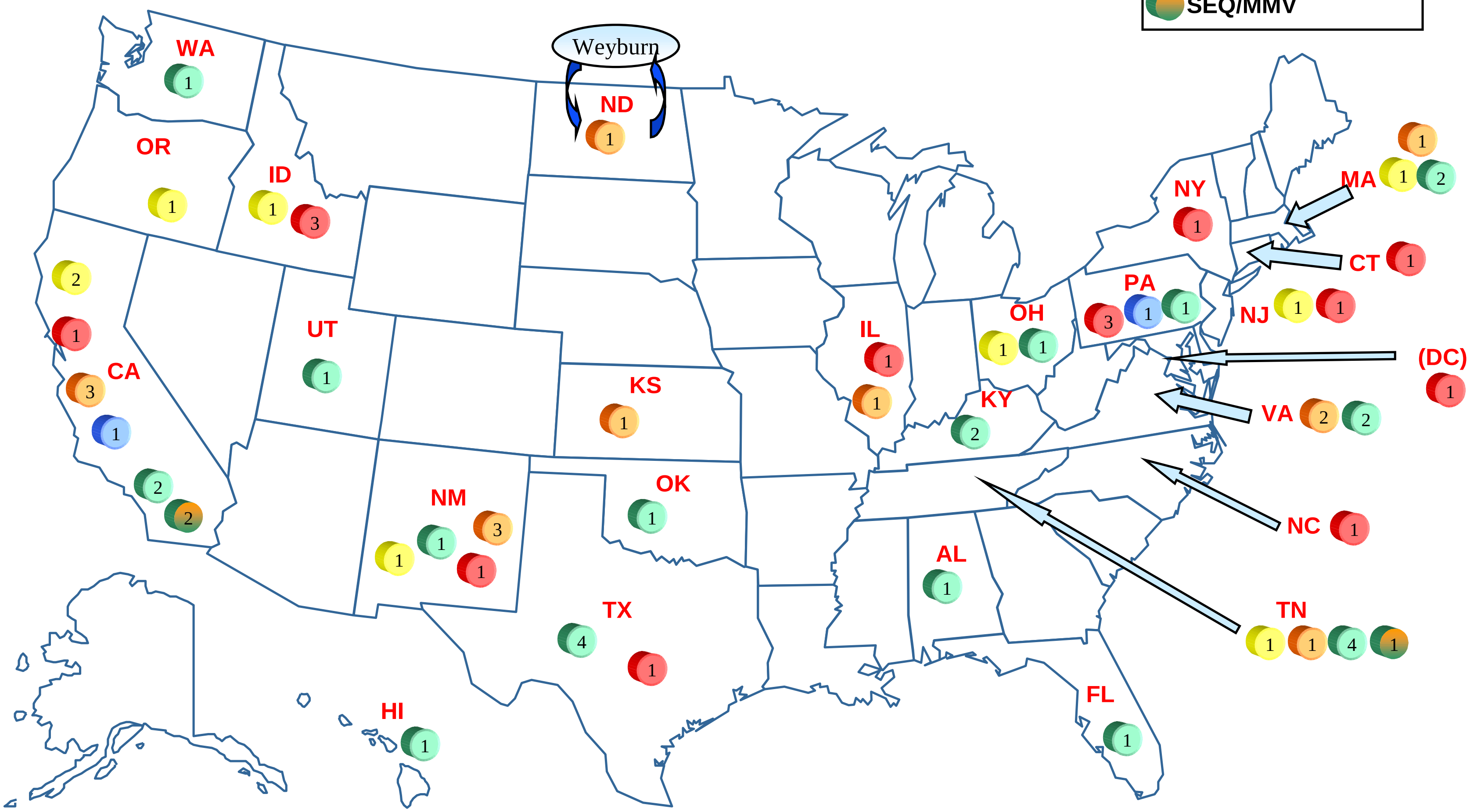
Carbon Sequestration Program Structure



Carbon Sequestration Projects

LEGEND

- Capture of CO_2
- MMV
- Sequestration
- Breakthrough
- Non-CO_2
- SEQ/MMV



*Includes BP. Doesn't include NETL

State Projects Summary Table

State/Project Title	Primary Contractor	Area
Alabama		
Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama	Alabama Geologic Survey	Sequestration
California		
Fuel-Flexible Gasification-Combustion Technology for Production of H_2 and Sequestration-Ready	GE Energy and Environmental Research Corporation	Breakthrough
Photoreductive Sequestration of CO_2 to Form C1 Products and Fuel	SRI International Corporation	Breakthrough
CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream	Nexant	Capture
Long term CO_2 Monitoring, Containment, and Storage Technology Development	LLNL	MMV
Geologic Carbon Sequestration monitoring and Modeling	LBNL	MMV
A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration	University of California, San Diego	MMV
Full-Scale Bioreactor Landfill	Yolo County	Non-CO_2
Feasibility of Large-Scale CO_2 Ocean Sequestration	Monterey Bay Aquarium Research Institute	Sequestration
Exploratory Measurements of Hydrate and Gas Compositions	LLNL	Sequestration
GEO-SEQ	LBNL	Seq/MMV
GEO-SEQ	LLNL	Seq/MMV
Connecticut		
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers	ALSTOM Power, Inc.	Capture
District of Columbia		
A Collaborative Project to Develop Technology for Capture and Storage of CO_2 from Large Combustion Sources	BP Corporation	Capture
Florida		
Ocean Carbon Sequestration (Offshore hydrate evaluation)	Naval Research Laboratory	Sequestration
Hawaii		
Environmental Permitting	PICHTR	Sequestration
Idaho		
Enhancement of CO_2 Emissions Conversion Efficiency by Structured Microorganisms (cyano-bacteria conversion of CO_2)	INEEL	Breakthrough
CO_2 Separation Using a Thermally Optimized Membrane	INEEL	Capture

NETL projects not included

State Projects Summary Table

State/Project Title	Primary Contractor	Area
Vortex Separation of CO_2	INEEL	Capture
Methodology for Conducting Probabalistic Risk Assessment of CO_2 Storage in Coal Beds	INEEL	Capture
Illinois		
CO_2 Capture for PC-Boiler Using Flue-gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options	ANL	Capture
CO_2 Reservoir Improvements	ANL	MMV
Kansas		
MIDCARB (Interactive Digital Carbon Atlas)	University of Kansas Center for Research	MMV
Kentucky		
Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production	University of Kentucky Research Foundation	Sequestration
Carbon Sequestration on Surface Mine Lands	University of Kentucky	Sequestration
Massachusetts		
Recovery & Sequestration of CO_2 from Stationary Comb. Systems by Photosynthesis of Microalgae	Physical Sciences, Inc.	Breakthrough
Development of a Carbon Management Geographic Information System for the US	MIT	MMV
International Collaboration on CO_2 Sequestration (CO_2 Ocean injection)	MIT	Sequestration
Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean	University of Massachusetts	Sequestration
North Carolina		
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents	Research Triangle Institute	Capture
North Dakota		
Weyburn Carbon Dioxide Sequestration Project	Natural Resources Canada - CANMET	MMV
New Jersey		
Advanced CO_2 Cycle Power Generation	Foster Wheeler	Breakthrough
Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO_2	Princeton University	Capture
New Mexico		
Mineral Sequestration of CO_2 - Chemical Dissolution Approaches	LANL	Breakthrough
Thermally Optimized Membranes	LANL	Capture

NETL projects not included

State Projects Summary Table

State/Project Title	Primary Contractor	Area
Sequestration of CO_2 in a Depleted Oil Reservoir	Sandia National Laboratories	MMV
Sequestration of CO_2 in a Depleted Oil Reservoir	LANL	MMV
Ecosystem Dynamics and Econ. Anal	LANL	MMV
Advanced Plant Growth (The plant-centric component)	LANL	Sequestration
New York		
Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO_2 Capture and Sequestration	Praxair, Inc.	Capture
Ohio		
Enhanced Practical Photosynthetic CO_2 Mitigation	Ohio University	Breakthrough
Experimental Evaluation of Chemical Sequestration of CO_2 in Deep Saline Formations	Batelle Columbus Laboratories	Sequestration
Oklahoma		
Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide	Oklahoma State University/Penn State University	Sequestration
Oregon		
CO_2 Mineralization	Albany Research Center	Breakthrough
Pennsylvania		
CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2	Media and Process Technology Inc.	Capture
Zero Emissions Power Plants Using SOFCs and Oxygen Transport Membranes	Siemens Westinghouse Power Corp. - Pittsburgh	Capture
An Integrated Modeling Framework for Carbon Management Technologies	Carnegie Mellon University	Capture
Capture and Use of Coal Mine Ventilation Air Methane	CONSOL Energy Inc.	Non-CO_2
Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams	Consol	Sequestration
Tennessee		
Chemical Fixation of CO_2 in Coal Combustion Products and Recycling Through Algal Biosystems	Tennessee Valley Authority	Breakthrough
Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil Fueled Electric Generation	Tennessee Valley Authority	Sequestration
Economic Evaluation of CO_2 Sequestration Technologies	Tennessee Valley Authority	MMV

NETL projects not included

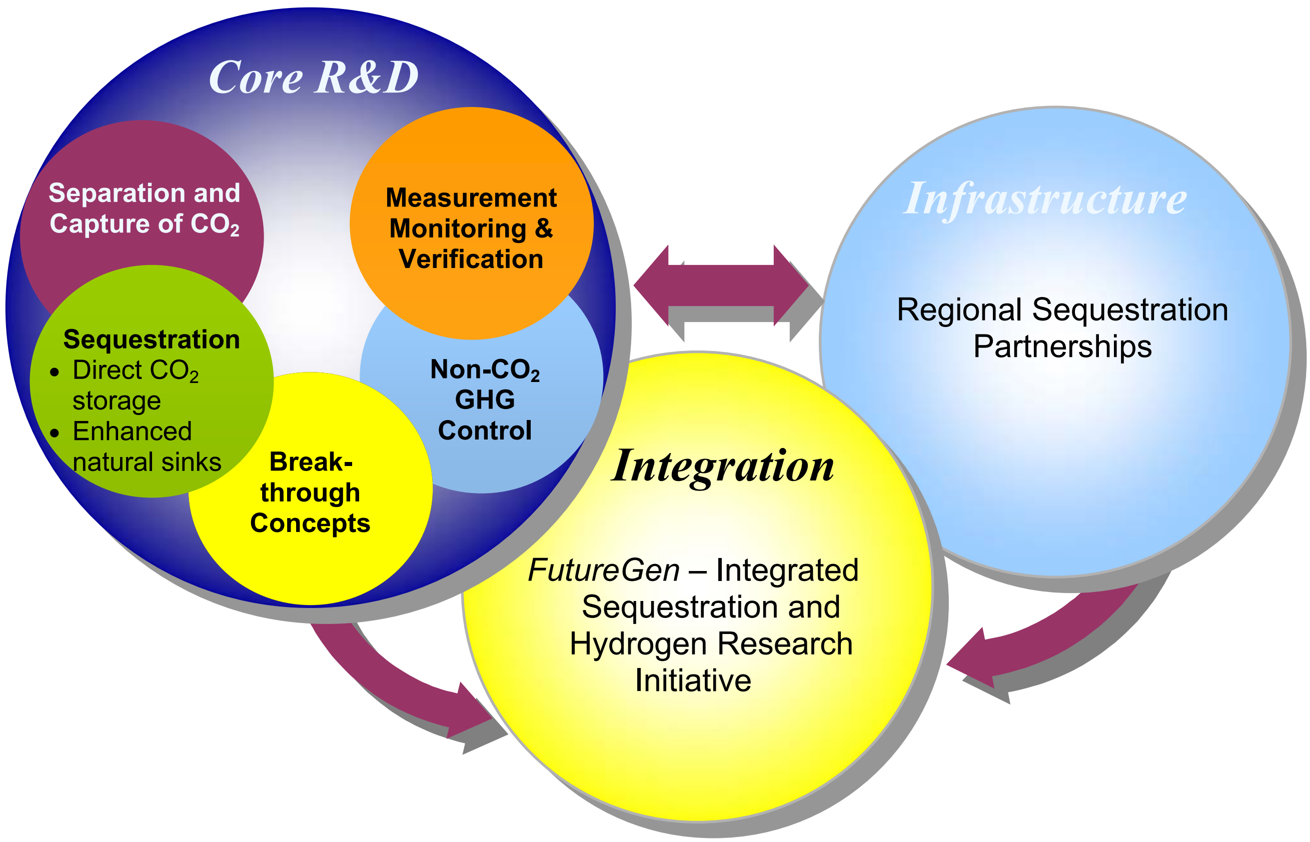
State Projects Summary Table

State/Project Title	Primary Contractor	Area
Effects of Temperature and Gas Mixing in Underground Coalbeds	Oak Ridge National Laboratory	Sequestration
Soil Enhances from Solid Wastes	ORNL	Sequestration
Enhanced Practical Photosynthesis Carbon Sequestration	ORNL	Sequestration
Geological Sequestration of CO_2 : GEO-SEQ	ORNL	Seq/MMV
Texas		
Carbon Dioxide Capture by Absorption with Potassium Carbonate	University of Texas at Austin	Capture
Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide	Texas Tech University	Sequestration
CO_2 Sequestration Potential of Texas Low-Rank Coals	Texas Engineering Experiment Station	Sequestration
Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers	University of Texas at Austin (BEG)	Sequestration
Enhancement of Terrestrial C Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians	Stephen F. Austin State University	Sequestration
Utah		
Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau	University of Utah	Sequestration
Virginia		
Natural Analogs for Geologic Sequestration	Advanced Resources International	MMV
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	MMV
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	MMV
Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services	Virginia Polytechnic Institute and State University	Sequestration
Washington		
Soil Enhances from Solid Wastes	PNNL	Sequestration

NETL projects not included

Carbon Sequestration

Technology Roadmap and Program Plan



March 12, 2003

U.S. DOE Office of Fossil Energy
National Energy Technology Laboratory

A Message to Our Stakeholders

On February 14, 2002 President Bush announced the **G**lobal **C**limate **C**hange **I**nitiative (**GCCI**) with the goal of significantly reducing the greenhouse gas intensity of the United States economy over the next 10 years, while sustaining the economic growth needed to finance investment in new, clean energy technologies. The GCCI calls for increased research and development investments to provide an improved basis for sound future decisions and for increased emphasis on carbon sequestration. In response to GCCI and related drivers, this document reflects important new developments.

- Measurement, monitoring, and verification (MM&V) of carbon sequestration has been prioritized along with carbon capture and carbon sequestration. Work in MM&V has been a part of the program from the outset, but the new structure represents increased emphasis.
- The program has adopted a revised strategic cost goal for carbon capture and sequestration: "create systems that capture at least 90% of emissions and result in less than a 10% increase in the cost of energy services." The revised goal puts the challenge for carbon sequestration in the context of minimizing the economic impact of greenhouse gas emissions mitigation.
- On November 21, 2002 Energy Secretary Spencer Abraham announced that the Department of Energy "intends to create a nationwide network of regional sequestration partnerships." The partnerships will seek to identify the most promising sequestration options in their area.
- The Program is collaborating with the National Academies of Science (NAS) to build a more robust portfolio of breakthrough concepts. In 2003 NAS conducted a workshop with experts from varied fields to identify specific and new R&D opportunities. The Program will use the results from the workshop in crafting a solicitation seeking breakthrough R&D projects.

> These partnerships - 4 to 10 across the country, each made up of private industry, universities, and state and local governments - will become the centerpiece of our sequestration program. They will help us determine the technologies, regulations, and infrastructure that are best suited for specific regions of the country.
>
> Energy Secretary Spencer Abraham
> November 21, 2002

Interaction with stakeholders is critically important to a successful R&D effort. In 2003 the program plans to engage stakeholder through the Second National Conference on Carbon Sequestration, the regional partnerships solicitation, the monthly carbon sequestration newsletter, conferences, and many other smaller outreach efforts.

This document is the current program vision of how to proceed in the development of carbon sequestration technology. It is both a roadmap and a program plan. The roadmap portion identifies RD&D pathways that lead to commercially viable carbon capture and sequestration systems. The program plan presents a course of action. Readers are invited to examine the document carefully and provide questions or comments to the contact persons listed on the back cover. Through a cooperative partnership of industry, academia, and government we have the best chance of success in developing viable carbon sequestration options.

GLOBAL CLIMATE CHANGE AND THE ROLE OF CARBON SEQUESTRATION

Alongside improved efficiency and low carbon fuels, carbon sequestration is a third option for greenhouse gas mitigation. It entails the capture and storage of carbon dioxide and other greenhouse gases that would otherwise be emitted to the atmosphere. The greenhouse gases can be captured at the point of emission, or they can be removed from the air. The captured gases can be stored in underground reservoirs, dissolved in deep oceans, converted to rock-like solid materials, or absorbed by trees, grasses, soils, or algae.

> ". . . our investment in advanced energy and sequestration technologies will provide the breakthroughs we need to dramatically reduce our [greenhouse gas] emissions in the longer term."
>
> President George W. Bush
> Global Climate Change Policy Book
> February 2002

The Global Climate Change Initiative (GCCI) set forth by President George W. Bush calls for an 18% reduction in the carbon intensity of the United States economy by 2012. Technology solutions that provide energy-based goods and services with reduced greenhouse gas emissions are the President's preferred approach to achieving the GCCI goal. The GCCI also calls for a progress review relative to the goals of the initiative in 2012, at which time decisions will be made about additional implementation measures for mitigating greenhouse gas emissions. By focusing on greenhouse gas intensity (the ratio of greenhouse gas emissions to economic output) as the measure of success, this strategy promotes vital climate change R&D while minimizing the economic impact of greenhouse gas stabilization in the United States.

Strong evidence is emerging that indicates greenhouse gas emissions are linked to potential climate change impacts. Figure 1 shows that the concentration of carbon dioxide in the atmosphere has increased rapidly in recent decades, and the increase correlates to the industrialization of the world. In 1992, the United States and 160 other countries ratified the Rio Treaty which calls for " . . . stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." An appropriate level of greenhouse gases in the atmosphere is still open to debate, but even modest stabilization scenarios eventually require a reduction in worldwide greenhouse gas emissions of 50-90% below current levels.

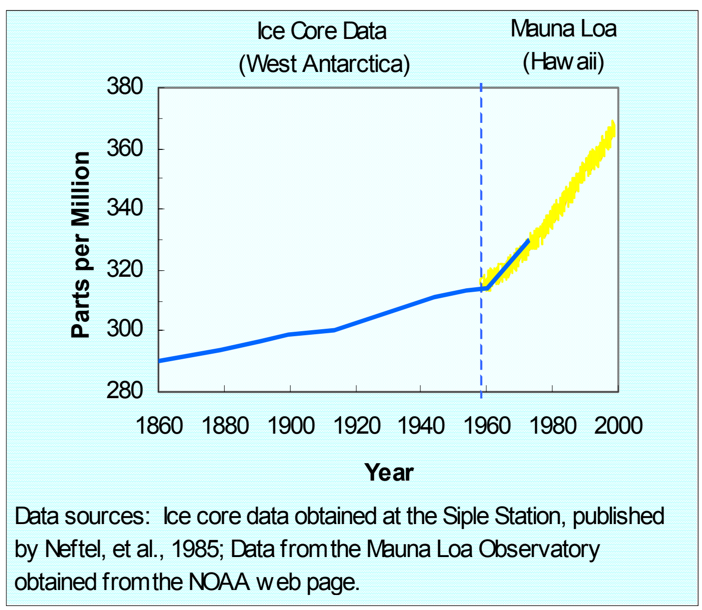


Figure 1. Atmospheric CO_2 Concentration is Increasing

In addition to national and international efforts, more than half of U.S. states have acted to pass voluntary or mandatory programs to limit net greenhouse gas emissions. For example:

> *Massachusetts:* requires the six oldest power plants (40% of in-state generation) to reduce CO_2 emissions to 10% below the average 1997-1999 levels by 2006
>
> *Oregon:* carbon emissions from new power plants must be at least 17% below the most efficient natural gas-fired plant operating in the U.S
>
> *New Hampshire:* carbon dioxide (CO_2) from fossil fuel burning steam electric power plants must be reduced to 1990 levels by 2010

Also, California, New Jersey, New Hampshire and Wisconsin have established greenhouse gas registries, and there is a large body of pending greenhouse gas legislation at the state, county, and municipal levels.

PUBLIC BENEFITS THROUGH TECHNOLOGY DEVELOPMENT

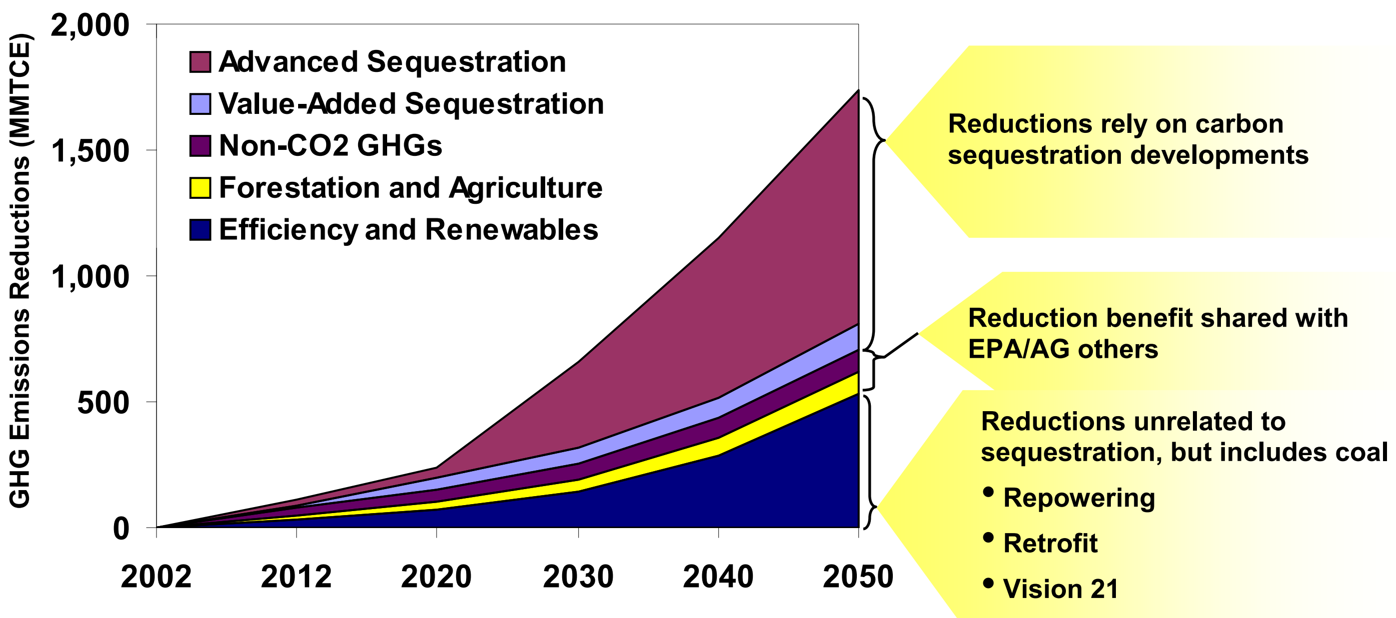
The Carbon Sequestration Program has performed an analysis of the role that carbon capture and storage can play in helping the United States and the world to stabilize and eventually reduce greenhouse gas emissions. The analysis shows that carbon sequestration can have a significant impact. On the capture side, roughly one third of the current U.S. greenhouse gas emissions come from power plants, oil refineries, and other large point sources, and that percentage will increase in the future with a trend toward increased refining and de-carbonization of fuels. On the storage side, the United States has vast forests and prairies, and is underlain by massive saline formations, depleting oil and gas reservoirs, and unmineable coal seams with the combined potential to store centuries worth of greenhouse gas emissions. Also, many options for CO_2 storage have the potential to provide value-added benefits. For example, tree plantings, no-till farming and other terrestrial sequestration options can prevent soil erosion and pollutant runoff into streams and rivers. CO_2 storage into depleting oil reservoirs and unmineable coal seams can enhance the recovery of crude oil and natural gas respectively while leaving a portion of the greenhouse gas sequestered. These value-added benefits have provided motivation for near term action and create interesting opportunities for integrated CO_2 capture and storage systems.

Hydrogen and Carbon Sequestration

Hydrogen-rich fuels and highly efficient electrochemical/mechanical drivers are at the center of many advanced energy system concepts. Leading technologies to produce hydrogen and other low-carbon fuels from natural gas and coal exhaust a highly pure stream of CO_2 as a natural part of their operation. These advanced systems represent an opportunity for low-cost CO_2 capture and provide a strong link between hydrogen energy systems and carbon capture and sequestration. **FutureGen**, a proposed $1 billion government/industry partnership to build and operate a coal-fired power generation and hydrogen production facility with advanced CO_2 capture and sequestration, will pursue this opportunity.

Figure 2 shows a reference case scenario for U.S. greenhouse gas emissions over the next fifty years compared to a reduced emissions scenario consistent with the Presidents GCCI goals through 2012 and a plausible stabilization scenario by mid century. Current annual U.S. greenhouse gas emissions are 12% higher than they were in 1992, and the Energy Information Administration (EIA) forecasts that U.S. CO_2 emissions will increase by an additional 34% over the next 20 years [Annual Energy Outlook 2002]. The projected increase is more significant when one considers that in their analysis, EIA assumes significant deployment of new energy technology through 2020, for example, a fourfold increase in electricity generation from wind turbines, a doubling of ethanol use in automobiles, and a 25% decrease in industrial energy use per unit of output. The need for greenhouse gas emissions reduction could be very large within a few decades and if potential for sequestration can be realized it can greatly reduce the cost of greenhouse gas emissions mitigation. For nearly any plausible scenario to greenhouse gas emissions stabilization, sequestration must account for at least 50% or more of the emissions reduction load.

Figure 2. Carbon Sequestration Technology is Needed to Reduce GHG Emissions



The DOE Carbon Sequestration R&D Program

Recognizing the importance of carbon sequestration, the U.S. DOE established the Carbon Sequestration Program in 1997. The program, which is administered within the Office of Fossil Energy and by the National Energy Technology Laboratory, seeks to move sequestration technology forward so that its potential can be realized and it can play a major role in meeting any future greenhouse gas emissions reduction needs. The program directly implements the President's GCCI, as well as several National Energy Policy goals targeting the development of new technologies, market mechanisms, and international collaboration to reduce greenhouse gas intensity and greenhouse gas emissions.

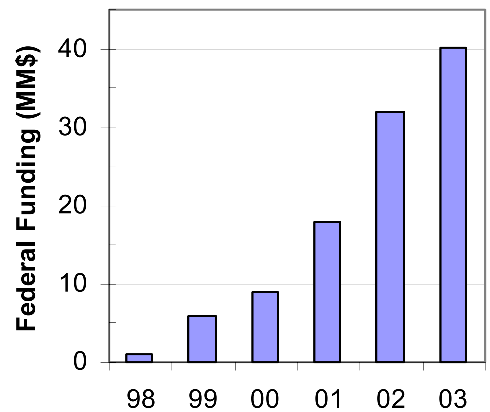


Figure 3. U.S. DOE Carbon Sequestration Program Budget

The Carbon Sequestration Program encompasses all aspects of carbon sequestration. The program has engaged federal and private sector partners that have expertise in certain technology areas, for example U.S. Department of Agriculture and electric utilities in terrestrial sequestration, U.S. Geologic Survey and the oil industry in geologic sequestration, and the National Academies of Science in breakthrough concepts. A strong focus is placed on direct capture of CO_2 emissions from large point sources and subsequent storage in geologic formations. These large point sources, power plants, oil refineries, and industrial processes, are the foundation of our economy. Reducing net CO_2 emissions from these facilities complements efforts to reduce emissions of particulate matter, sulfur dioxide, and nitrous oxides and represent a progression toward fossil fuel production, conversion, and use with no detrimental environmental impacts. In addition, measurement, monitoring, and verification (MM&V) is emerging as an important cross-cutting component for CO_2 capture and storage systems, and terrestrial offsets are a vital component of cost-effective near-complete elimination of net CO_2 emissions from many large point sources.

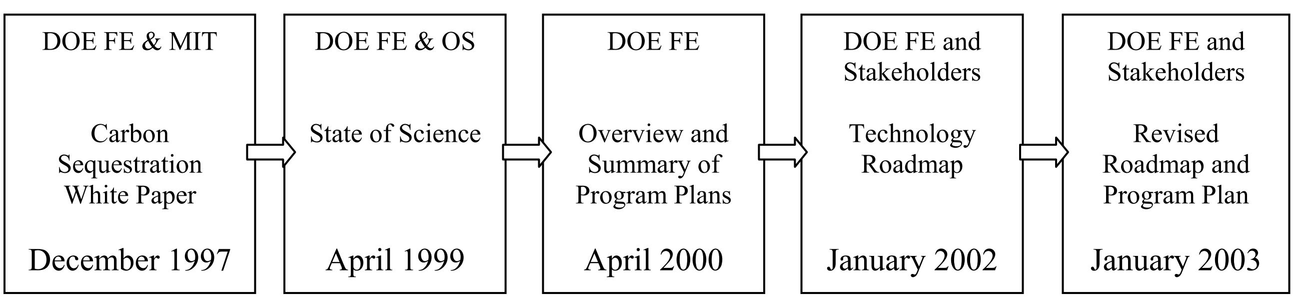


Figure 4. Roadmap Evolution

VISION STATEMENT

Possess the scientific understanding of carbon sequestration options and provide cost-effective, environmentally-sound technology options that ultimately lead to a reduction in greenhouse gas intensity and stabilization of overall atmospheric concentrations of CO_2.

Overarching Goals

- By 2006 develop instrumentation and measurement protocols for direct sequestration in geologic formations and for indirect sequestration in forests and soils that enable the implementation of wide-scale carbon accounting and trading schemes.
- By 2008, develop to the point of commercial deployment systems for advanced indirect sequestration of greenhouse gases that protect human and ecosystem health and cost no more than $10 per metric ton of carbon sequestered, net of any value-added benefits.
- By 2009, begin demonstration of advanced carbon storage in a geologic formation at large scale (>1MMTCO_2/year). Storage options include value-added (enhanced oil recovery, enhanced coal bed methane recovery, enhanced gas recovery) and non-value added (depleted oil/gas reservoirs and saline aquifers).
- By 2010 develop instrumentation and protocols to accurately measure, monitor, and verify both carbon storage and the protection of human and ecosystem health for carbon sequestration in terrestrial ecosystems and geologic reservoirs. MM&V systems should represent no more that 10% of the total sequestration system cost.
- By 2012, develop to the point of commercial deployment systems for direct capture and sequestration of greenhouse gas emissions from fossil fuel conversion processes that protect human and ecosystem health and result in less than a 10% increase in the cost of energy services, net of any value-added benefits.
- Enable sequestration deployments to contribute to the President's Global Climate Change Initiative goal of an 18% reduction in the greenhouse gas intensity of the United States economy by 2012.
- Provide a portfolio of commercial ready sequestration systems and also one to three breakthrough technologies that have progressed to the pilot test stage for the 2012 assessment under the Global Climate Change Initiative.
- By 2018, develop to the point of commercial deployment systems for direct capture and sequestration of greenhouse gas and criteria pollutant emissions from fossil fuel conversion processes that result in near-zero emissions and approach a no net cost increase for energy services, net of any value-added benefits.

Figure 5 shows how the different program elements contribute to the overarching program goal of commercial ready sequestration options. The Program is strongly focused on direct CO_2 capture from fossil fuel conversion systems and CO_2 sequestration in geologic formations. But also contains significant efforts in terrestrial and other indirect sequestration approaches. All are encompassed within the program elements shown in Figure 5. Major program efforts are described below.

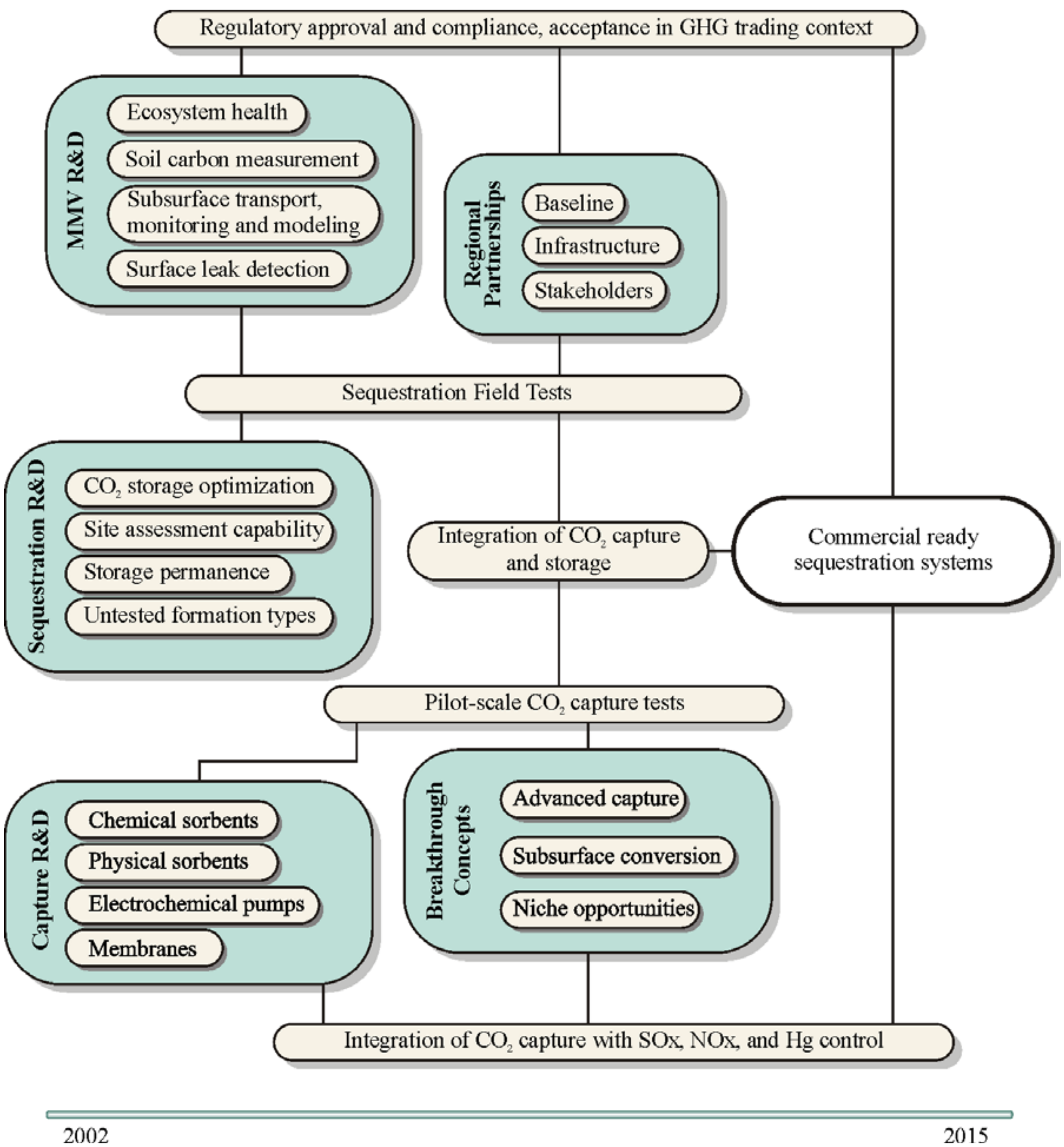
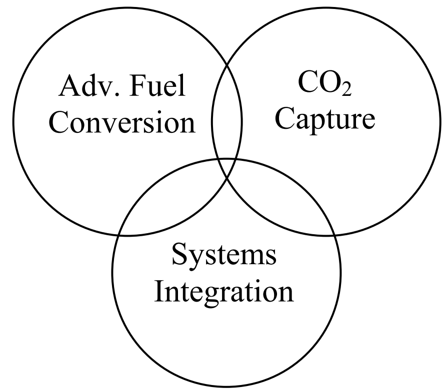


Figure 5. Carbon Sequestration Program Roadmap Diagram

CO_2 CAPTURE

The Carbon Sequestration Program funds capture R&D projects covering a wide range of technology areas including: amine absorbents, carbon adsorbents, membranes, sodium and other metal-based sorbents, electrochemical pumps, hydrates, and mineral carbonation. Presently, component performance is being evaluated at the laboratory or pilot scale. The majority of the work is funded through competitively awarded cost-shared projects with industry.



Research into a CO_2 capture technology occurs within the context of the energy conversion system(s) to which it is to be applied. There is a strong synergistic link between improved efficiency of fossil fuel conversion systems and carbon capture; the cost of carbon capture per unit of product is less for a more efficient process. Also, advanced fuel conversion technologies such as gasification, oxygen combustion, electrochemical cells, advanced steam reforming, and chemical looping produce a CO_2-rich exhaust stream that is highly amenable to CO_2 sequestration – or ready for transport and storage. Some CO_2 capture technologies can be applied to a wide range of CO_2-containing process streams. Others are more specialized. The program monitors developments in relevant research areas and evaluates the impact of advances on the priorities within the capture portfolio.

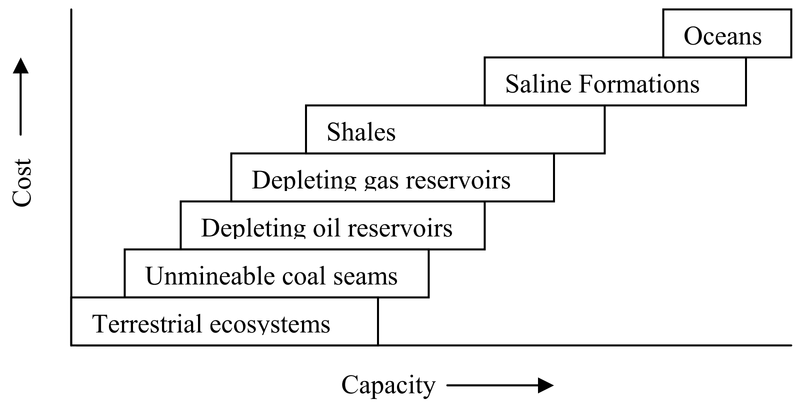
The cost and efficiency performance of CO_2 capture can be significantly improved through close consideration of systems integration issues, including integration of CO_2 capture and storage. For example, heat and pressure integration between CO_2 capture and the rest of the fossil fuel conversion systems can reduce parasitic steam and CO_2 recompression loads. Also, combining or integrating CO_2 capture with SO_x, NO_x, and mercury control can eliminate or lessen the need for scrubbers and other emissions abatement systems. Systems integration is being explored through laboratory and pilot scale experiments, and, ultimately in the commercial scale FutureGen demonstration.

SEQUESTRATION

This program element encompasses all forms of carbon storage, including storage in terrestrial ecosystems, geologic formations, and oceans. Through the development of optimized field practices and technologies, the program seeks to quantify and improve the storage capacity of all potential reservoirs and to expand the number and type of reservoirs in which carbon storage is commercially viable.

Increasing the carbon uptake in terrestrial ecosystems is highly correlated with fundamental agricultural and forestry goals of encouraging productive plant growth with sustainable harvests. The DOE sequestration program is focused on the integration of energy production, conversion, and use with land reclamation. Current projects include a large-scale demonstration of reforesting recently mined lands in Virginia, West Virginia, Kentucky and a smaller-scale demonstration integrating terrestrial sequestration with energy production by employing the use of coal combustion byproducts.

The program seeks to lower the cost and increase the capacity of the various CO_2 sequestration options



In the area of geologic sequestration, there are several types of formations in which CO_2 can be stored including: depleting oil reservoirs, depleting gas reservoirs, unmineable coal seams, saline formations, shale formations with high organic content, and others. Each type of formation has its own mechanism for storing CO_2 and a resultant set of research priorities and opportunities. The program has initiated a number of field tests where a small amount of CO_2 will be injected into a formation and its behavior studied. A goal of the Regional Partnerships initiative is to identify additional opportunities for both terrestrial and geologic sequestration field validation tests. Also, the program is investing in research facilities at NETL that will enable it to simulate the extreme environments in underground formations, conduct experiments, and develop a better understanding of the fundamental principles that will drive optimal CO_2 injection practices.

Compared to terrestrial ecosystems and geologic formations, the concept of ocean sequestration is in a much earlier stage of development. Ocean sequestration has huge potential as a carbon storage sink, but the scientific understanding to merit ocean sequestration as a real option is not available. A small level of funding is provided to leading researchers in this area to develop the necessary scientific understanding on feasibility of ocean sequestration. Work is focused on assessing the environmental impacts of CO_2 storage. The program is also funding laboratory experiments aimed at learning more about the basics of CO_2 drop behavior in an ocean environment and also the formation and behavior of CO_2 hydrates.

MEASUREMENT, MONITORING, AND VERIFICATION (MM&V)

MM&V is defined as the capability to measure the amount of CO_2 stored at a specific sequestration site, to monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the CO_2 is stored and unharmful to the host ecosystem. MM&V capability will ensure safe permanent storage, will reduce the risk associated with buying or selling credits for sequestered CO_2, and will help satisfy regulators and local government officials who must approve large sequestration projects. MM&V will also provide valuable feedback for continual refinement of injection and management practices.

The program is pursuing MM&V technology for a broad range of sequestration options including terrestrial ecosystems, geologic formations, and oceans. MM&V for terrestrial ecosystems includes 3D videography methods for modeling and tracking above ground carbon and infield technology to measure soil and other below ground carbon.

In geologic sequestration, the program is developing both below-ground and above-ground MM&V technology. Work in below-ground MM&V systems draws upon a significant capability developed for fossil resource exploration and production. Options include surface to borehole seismic, micro-seismic, and cross well electromagnetic imaging devices. The area of above-ground MM&V is less mature and is focused on detecting leaks from a geologic reservoir.

The MM&V program element also includes the development of protocols and methodologies for calculating the net avoided CO_2 emissions from systems with carbon capture, specifically considering and comparing different levels of parasitic losses and methods for replacing capacity.

BREAKTHROUGH CONCEPTS

The program is pursuing revolutionary sequestration approaches with potential for low cost, high permanence, and large global capacity. A guiding principal is to mimic and harness processes found in nature that convert CO_2 to another carbonaceous substance, for example photosynthesis and mollusk shell formation. A priority area of study is subsurface CO_2 conversion to enhance geologic sequestration.

The program is funding two major efforts in this area. First are facilities and experiments at the Carbon Sequestration Science Focus Area (CSSFA). The CSSFA uses in-house resources at NETL to conduct research in a number of sequestration areas with a focus on high technical risk concepts. A second and complementary effort is a collaboration with the National Academies of Science (NAS) to expand the number of projects from industry and academia. In 2003 NAS conducted an experts' workshop to identify R&D opportunities in the area of breakthrough concepts. The program will use the results from the workshop in crafting a solicitation for R&D projects. Once proposals are received, an NAS committee will evaluate the scientific, technical, engineering and environmental merits of each.

The Carbon Sequestration Science Focus Area at NETL

The CSSFA performs research and development in areas important to the program but with technical risk too high for industry. The following are recent success stories.

Turning a Conventional CO_2 Capture Technology into an Advanced One. **McMahan Gray** has developed a fundamentally straightforward method for implanting amines onto a variety of solid substrates. Conventional water/liquid amine capture systems require significant amounts of energy during the CO_2 absorption/desorption cycle. The solid amines fabricated with this new method have the potential to capture CO_2 with much less energy. The National Energy Technology Laboratory has filed a record of invention (DE09/966,570).

Understanding and Improving CO_2 Absorption on Coal. Early field tests of CO_2 storage in unmineable coal seams were producing results that departed from theoretical projections. **Karl Schroeder** has achieved a much greater predictive ability by properly incorporating the fact that coals increase in volume (swell) when they are exposed to CO_2 and absorb it onto their pore surfaces. Dr. Schroeder's insight will help practitioners to optimize CO_2 sequestration via enhanced coal bed methane.

REGIONAL SEQUESTRATION PARTNERSHIPS

The regional diversity of CO_2 sources and storage options calls for a diverse portfolio of strategies for carbon management. The Program seeks to engage local government agencies and non-governmental organizations, along with the research community and private sector participants, in a number of Regional Sequestration Partnerships centered in areas of the country with potential for CO_2 capture and storage.

These partnerships will promote the development of a framework and infrastructure necessary for the validation and deployment of carbon sequestration technologies. The partnerships will baseline the region for CO_2 sources and sinks and will establish MM&V protocols. They will also address regulatory, environmental, and outreach issues associated with priority sequestration opportunities in the region. In FY 2003 the program plans to make 4-10 phase 1 regional partnership awards. In FY 2005, the program plans to advance to a second phase in which sequestration opportunities identified by the Phase I regional partnerships could serve as settings for technology field validation tests.

FUTUREGEN – AN INTEGRATED SEQUESTRATION AND HYDROGEN RESEARCH INITIATIVE

Contingent upon funding approval, in FY 2003 the Program plans an Integrated Sequestration and Hydrogen Research Initiative that couples CO_2 separated and captured from a coal-fired power plant with sequestration in a geologic formation. The project will focus on large systems, of greater that one million metric tons of CO_2 sequestered per year, and concepts where CO_2 capture and geologic sequestration are integrated. The project is a logical and required extension of the base Carbon Sequestration R&D Program and will, if successful, achieve the following:

- Design, construct, and operate a nominal 275-megawatt (net equivalent output) prototype plant that produces electricity and hydrogen with near-zero emissions. The size of the plant is driven by the need for producing commercially-relevant data, including the requirement for producing one million metric tons per year of CO_2 to adequately validate the integrated operation of the gasification plant and the receiving geologic formation.

- Sequester at least 90 percent of CO_2 emissions from the plant with the future potential to capture and sequester nearly 100 percent.

- Prove the effectiveness, safety, and permanence of CO_2 sequestration.

- Establish standardized technologies and protocols for CO_2 MM&V.

- Validate the engineering, economic, and environmental viability of advanced coal-based, near-zero emission technologies that by 2020 will: (1) produce electricity with less than a 10% increase in cost compared to non-sequestered systems; (2) produce hydrogen at $4.00 per million Btus (wholesale), equivalent to $0.48/gallon of gasoline, or $0.22/gallon less than today’s wholesale price of gasoline.

NON-CO_2 GREENHOUSE GASES

Because non-CO_2 greenhouse gases (e.g., methane, N_2O, and high global warming potential gases) have significant economic value, emissions can often be captured or avoided at low net cost. The program is focused on areas where non-CO_2 greenhouse gas abatement is integrated with energy production, conversion, and use. Two projects are currently being funded: (1) minemouth ventilation methane mitigation [Consol, Inc.] and (2) impermeable membranes for landfill gas recovery [IEM, Inc.]. The Program is working with the United States Environmental Protection Agency (EPA) to assess the role that non-CO_2 greenhouse gas emissions abatement actions can play in a nationwide strategy for reducing greenhouse gas emissions intensity. The Program is also working with EPA to identify priority areas for research and development.

EDUCATION AND OUTREACH

The notion of capturing and sequestering carbon dioxide and other greenhouse gases is relatively new, and many people are unaware of its role as a greenhouse gas reduction strategy. Increased education and awareness are needed to achieve acceptance of carbon sequestration by the general public, regulatory agencies, policy makers, and industry and thus enable future commercial deployments of advanced technology. The following activities highlight the program's education and outreach efforts:

- Carbon Sequestration Webpage at the NETL site
- Monthly sequestration newsletter
- The 2002 Sequestration Technology Roadmap
- The First National Conference on Carbon Sequestration (May 2001) and the Second National Conference on Carbon Sequestration (planned for May 2003)

In addition the program management team participates in technical conferences through presentations, panel discussions, break out groups, and other formal and informal venues. These efforts expose professionals working on other fields to the technology challenges of sequestration and also enable examination of some of the more detailed issues underlying the technology. Examples include the Terrestrial Carbon Sequestration "Hands-On" Workshop for the Appalachian Coal & Electric Utilities Industries held in November 2001 and sequestration-related symposia organized at recent meetings of the American Geophysical Union and American Association for the Advancement of Science.

The Carbon Sequestration Newsletter

Started in July 2001, the newsletter provides brief summaries of sequestration-related news, events, recent publications, and legislative activity. Subscription has grown to over 800. In August of 2002, NETL issued the annual newsletter index, which is a useful tool for finding articles and news pieces over the past year. Back issues and the index can be downloaded from the NETL site.

You can register to receive the newsletter (it is free). Go to:

http://www.netl.doe.gov/coalpower/sequestration/index.html

and click on "get the news."

As with any new technology, there are environmental issues associated with carbon sequestration that need to be explored, understood, and addressed. The level of uncertainty is higher for some sequestration options than for others. A significant portion of the program's R&D portfolio is aimed at improved understanding of potential environmental impacts. In concert with R&D, the program seeks to engage NGO's, federal, state, and local environmental regulators to raise awareness of what the program is doing in this area, and the priority it places on systems that preserve human and ecosystem health. Some of the program's R&D projects have their own outreach component. For example, the cost-shared project with the Nature Conservancy on measuring, monitoring, and verification in terrestrial ecosystems has helped the program to engage Non-Governmental Organizations and the environmental community. Also, the Regional Partnerships will enhance technology development but also engage regulators, policy makers, and interested citizens at the state and local level. Successful outreach entails two-way communications, and the program will consider concerns voiced at outreach venues and continually assess the adequacy and focus of the current R&D portfolio.

INTERNATIONAL COLLABORATION

Recognizing that the needs for new science and technologies to reduce greenhouse gas emissions is a global concern, the Carbon Sequestration Program is deeply engaged in building international collaboration and partnerships throughout the world. The following are prominent examples of the program's work with international entities. As global interest and funding in carbon sequestration research increases, these collaborations will likely expand

International Energy Agency The DOE is a participating member in the International Energy Agency's Greenhouse Gas Research and Development Programme (IEA/GHG). The program was started in 1991 and is arguably the most well respected international effort in the greenhouse gas R&D arena. It is funded by 18 international members including the European Union, Australia, Canada, Italy, Japan, Norway, and eight private sector sponsors. The Programme evaluates greenhouse gas mitigation technologies; disseminates information via a bi-monthly newsletter "Greenhouse Issues" and a web-site; and organizes international expert workshops and conferences, most prominently the biannual Greenhouse Gas Technology Conference. Information can be found at http://www.ieagreen.org.uk/

The Carbon Capture Project (CCP) In 2001, the DOE awarded a cooperative agreement with British Petroleum (BP) Corporation to develop innovative CO_2 capture technologies. BP is the operating agent for the CCP, a consortia of eight major international energy companies (ChevronTexaco, Norsk Hydro, ENI, PanCanadian, Royal Dutch/Shell, Statoil and Suncor Energy) that are collectively funding the project from the industry side. The CCP aims to develop new, breakthrough technologies to reduce the cost of carbon dioxide separation, capture, transportation and sequestration from fossil fuel combustion streams by at 50% for existing energy facilities, and by 75% for new energy facilities, by the end of 2003 compared to currently available alternatives. Additional information can be found at http://www.co2captureproject.org/

Canada The US DOE Sequestration Program is co-funding, along with Pan Canadian Resources, Dakota gasification, and the Department of Natural Resources of Canada, a project to sequester carbon as a part of an enhanced oil operation in Weyburn, Canada in southeastern Saskatchewan. The collaboration was made possible through a negotiated Annex to the provisions of the Implementing Arrangement between U.S. DOE and the Department of Natural Resources of Canada for Cooperation in the Area of Fossil Fuels, signed on February 1, 2000. Additional information can be found at http://www.ieagreen.org.uk/weyburn4.htm

Norway Roughly one million metric tons per year of vented CO_2 from a natural gas processing platform in the north sea is being captured and injected into the Utsira saline aquifer formation. The Sliepner project was spearheaded by Statoil which sought to take advantage of a Norwegian CO_2 emissions tax credit. Working with the IEA/GHG R&D Programme, the carbon sequestration program has provided funding for the Saline Aquifer CO_2 Storage (SACS) project--a robust measurement, verification and transport modeling activity to compliment and enhance the injection experiment. This work will ensure that as much as possible is learned. Additional information can be found at http://www.ieagreen.org.uk/sacshome.htm

CARBON SEQUESTRATION TECHNOLOGY ROADMAP AND SUPPORTING PROGRAM ACTIVITIES

The following tables provide more detailed information about sequestration technology pathways and supporting program activities.

Table 1 is a top-level roadmap plan for four primary technology thrusts: CO_2 capture, sequestration, MM&V, and breakthrough concepts. For each technology thrust, Table 1 presents goals, pathways, and metrics for success.

Tables 2, 3, and 4 present Level II roadmaps for capture, sequestration, and MM&V. These tables describe the current status the pathways within each technology thrust area, present a list of R&D opportunities specific to each pathway, and also present crosscutting R&D opportunities. Program goals that apply to each pathway are defined, and a list of relevant projects from the program's R&D portfolio aimed are presented.

Table 5 presents four new program initiatives: the collaboration with the National Academies of Science (NAS), the regional partnerships initiative, *FutureGen* – an integrated sequestration and hydrogen research initiative, and the MM&V program. The initiatives are described and metrics for success defined for each.

A Level II roadmap table is not presented for Breakthrough Concepts. A major focus of the NAS collaboration and the subsequent solicitation will be to identify pathways and projects in that area. The 2004 Roadmap will supply a Level II table for breakthrough concepts based on the results of the NAS workshop.

A Level II roadmap table is also not presented for Non-CO_2 greenhouse gas abatement. Results from ongoing collaborative work with the U.S. EPA will be presented in next year's roadmap.

Table 1. Top Level Carbon Sequestration Roadmap					
	Goals	**Pathways**	**Metrics for Success**		
			2004	**2007**	**2012**
Capture	• Lower the capital cost and energy penalty associated with capturing CO_2 from large point sources	• Post-combustion capture • Oxygen combustion • Pre-combustion capture • Chemical looping	Retrofits: 30% reduction in capital cost and energy load below 2002 technology	New builds: 75% reduction in capital cost and energy load below 2002 technology	10% increase in cost of energy proven for direct capture concept
Sequestration	• Expand the number and type of carbon sequestration opportunities in the United States and the world • Lower the cost and optimize the value-added benefits associated with CO_2 storage • Develop field practices to minimize seepage from geologic storage sites. • Develop management practices to promote permanence at terrestrial sequestration sites • Develop capability to assess capacity for carbon storage	• Depleting oil reservoirs • Unmineable coal seams • Saline formations • Enhanced terrestrial uptake • Ocean fertilization • Novel geologic formations • Ocean injection	Demonstrate net CO_2 storage in depleting oil reservoir of 10,000 scf CO_2 per barrel of oil recovered (increase from typical current value of 2,000 scf CO_2/bbl)	Demonstrate net CO_2 storage in an unmineable coal seam of 3 scf CO_2 per scf CBM recovered Demonstrate CO_2 injection into saline formations via horizontal or multilateral wells	Global CO_2 seepage verified at less than 0.01% per year
MM&V	• Develop technologies to accurately baseline terrestrial ecosystems, geologic formations, and ocean systems • Develop technologies to assess ecological impacts of carbon storage • Develop capability to detect leaks or deterioration in CO_2 storage • Develop methods for calculating net avoided emissions from CO_2 capture, transport, and storage systems	• Advanced soil carbon measurement • Remote sensing of above-ground CO_2 storage and leaks • Detection and measurement of CO_2 in geologic formations • Fate and transport models for CO_2 in geologic formations • Ecosystem flux models	Instrumentation & measurement protocols for geologic formations, forests, and soils that enable carbon accounting and trading and maximize credits achievable	Capability to ensure the permanence of GHG storage in geologic, ocean and terrestrial sinks and to assess the protection of human and ecosystem health	MMV represents no more than 10% of total sequestration cost
Breakthrough concepts	• Develop revolutionary approaches to carbon capture and storage that have the potential to address the level of reductions in greenhouse gas emissions consistent with long term atmospheric stabilization	• Advanced CO_2 capture, including biochemistry and enzymes • Bio-accelerated sequestration subsurface • CO_2 neutralization subsurface • Niches –circumstances where it is very easy or convenient to sequester some carbon	Achieve orders of magnitude improvement in mineralization reaction rates and energy needs at pilot scale	Identify breakthrough direct capture and storage with potential for less than 10% increase in cost of energy based upon lab scale results	Lab scale concept for indirect capture/conversion at 10 $/ton 10% increase in cost of energy proven for direct capture concept

<table>
<tr><th colspan="6">Table 2. Level II - CO_2 Capture Roadmap and Program Plan</th></tr>
<tr><th colspan="4">Roadmap</th><th colspan="2">Plan</th></tr>
<tr><th rowspan="2">Path ways</th><th rowspan="2">Current Technology Status</th><th colspan="2">R&D Opportunities</th><th rowspan="2">Pathway-level Goals</th><th rowspan="2">Supporting Program R&D Projects</th></tr>
<tr><th>Pathway-specific</th><th>Cross-cutting</th></tr>
<tr><td>Pre-combustion de-carbonization</td><td>10 oxygen-fired gasifiers in operation in the United States today. Syngas from an oxygen-fired gasifier can be shifted to provide a stream of primarily H_2 and CO_2 at 400-800 psi. Glycol solvents can capture CO_2 and be regenerated via flash (no steam use) to produce pure CO_2 at 15-25 psi.</td><td>• Advanced amine absorption
• Develop advanced physical or chemical absorption technology
• Improved CO_2/H_2 membranes</td><td rowspan="4">Heat and pressure integration with other system components.

Integration/ combination with NO_x, SO_x, Hg, and particulate matter control

Hybrid oxyfuel/post combustion capture systems

Integrate capture and geologic storage</td><td>2007 75% reduction in capital cost and energy load for CO_2 capture from new builds compared to 2002 technology</td><td>• Selective ceramic membrane [MPT]
• CO_2 hydrate capture process [Bechtel]
• High-temperature polymer membrane [INEEL, LANL]</td></tr>
<tr><td>Oxygen-fired combustion</td><td>No oxygen-fired PC plants in commercial operation. Current minimum CO_2 recycle is 5 lbs CO_2 per lb coal feed. 90% pure CO_2 is produced from the boiler at 10-15 psi. Oxygen combustion requires roughly three times more oxygen per kWh of electricity generation than gasification.</td><td>• O_2-selective membranes
• Advanced cooling cycles
• Compact boilers and turbines that can operate at high temperature and pressure</td><td>2004 pilot scale demo of potential for 75% reduction in CO_2 recycle requirements</td><td>• Advanced oxyfuel boiler design [Praxair, Alstom Power – parallel projects]</td></tr>
<tr><td>Post-combustion capture</td><td>300 GW of PC boiler capacity in the United States. Flue gas from a PC boiler is exhausted at 10-15 psi and contains 12-18 volume percent CO_2. Amine scrubbing with CO_2 compression to 1200 psi costs roughly 2000 $/kW and reduces the net power plant output by 12.5%.</td><td>• Advanced amine absorption
• Physical sorbents
• CO_2 selective membranes
• Sorbent/membrane
• Advanced gas/liquid contactors</td><td>2004 pilot scale demo of potential for 30% reduction in steam consumption per CO_2 captured below 2002 amine technology.</td><td>• Sodium/magnesium-based chemical sorbents [RTI]
• Electrochemical pump [CCP, CSSFA]
• Amine enriched adsorbents [CSSFA]
• Carbonate-based CO_2 capture [CSSFA]</td></tr>
<tr><td>Advanced conversion</td><td>There are a limited number of promising ideas in this area. None of them are at the commercial or demonstration phase.</td><td>• Chemical looping</td><td>2007 pilot scale demo of potential for capital and operating cost 20% higher than a 2002 PC boiler.</td><td>• Metal oxide materials for chemical looping fuel conversion process [TDA research]</td></tr>
</table>

<table>
<tr><th colspan="7">Table 3. Level II - Sequestration Roadmap and Program Plan</th></tr>
<tr><th colspan="5">Roadmap</th><th colspan="2">Plan</th></tr>
<tr><th rowspan="2"></th><th rowspan="2">Current Status</th><th colspan="2">R&D Opportunities</th><th rowspan="2">Pathway-level Program Goals</th><th rowspan="2">Supporting Program R&D Projects</th></tr>
<tr><th>Pathway specific</th><th>Crosscut</th></tr>
<tr><td>Depleting oil reservoirs</td><td>32 million tons of CO_2 per year injected into depleting oil reservoirs in the U. S. as a part of enhanced oil operations, 10 % from anthropogenic sources. Current practices are not directed toward optimizing CO_2 storage, typical storage rate is 2,000 scf CO_2 per bbl oil recovered.</td><td>• Modeling and testing for maximum long-term storage of CO_2 with EOR</td><td rowspan="4">Integrated database of domestic saline formations, depleting and depleted oil and gas wells, an coal seams containing data related to CO_2 storage potential

Integrate knowledge and understanding from sequestration field test and capacity modeling with transport modeling efforts in MM&V

Develop methodologies and strategies for produced water</td><td>2004 Demonstrate net CO_2 storage in depleting oil reservoir of 10,000 scf CO_2 per barrel of oil recovered (5-fold increase over current operations)</td><td>• Develop a three dimensional model of an existing depleting oil field to assess co-optimization of CO_2 storage and oil/gas recovery [LBNL]</td></tr>
<tr><td>Unmineable coal seams</td><td>Coal bed methane is the fastest growing source of domestic natural gas supply, 1.6 TCF produced in 2001. No commercial deployments of CO_2-enhanced CBM recovery. CO_2 must compete with nitrogen as an enhancing agent.</td><td>• Improve understanding of injection of CO_2 and CO_2/N_2 mixtures
• Understand swelling in domestic coals
• Advanced injection well configuration</td><td>2007 Demonstrate net CO_2 storage in an unmineable coal seam of 3 scf CO_2 per scf CBM recovered (2-fold increase over current operations)</td><td>• Field experiment in San Juan, NM, 4 million scf CO_2 per day [ARI/Burlington Resources]
• Field test of slant hole drilling, Southern Virginia, ## scf CO_2 per day [Consol, Inc.]
• CO_2 storage capacity model of Black Warrior region in Alabama [AGS]</td></tr>
<tr><td>Saline formations</td><td>Several large saline formations underlie the United States, but there is no injection of CO_2 into them. One million tons CO_2 per year is being injected in the saline formation at the Sliepner natural gas production field in the North Sea.

A significant body of data on domestic brine formations has been compiled by NETL, the University of Texas at Austin, and others.</td><td>• CO_2 flow modeling for diverse formations
• Studies of CO_2 in brine chemical mineral systems
• Horizontal and multilateral wells for improved CO_2 injectivity</td><td>2007 Demonstrate CO_2 injection into domestic saline formations via horizontal or multilateral wells</td><td>• Perform detailed CO_2 storage capacity assessments for (1) the Mt. Simon formation underlying the Midwestern U.S. [AEP, BCL] (2) the Frio Brine formation near Houston, TX. [LBNL], and (3) formations underlying the Colorado Plateau [University of Utah]
• Investigate hydraulic fracturing to improve permeability [Texas Tech University]
• Study CO_2 carbonation reactions in simulated brine environments [CSSFA]</td></tr>
<tr><td>Novel geologic formations</td><td>Promising but untested reservoir types have significant carbon storage capacity and the potential for value-added hydrocarbon production with CO_2 storage.</td><td>• depleting gas reservoirs
• organically rich shales</td><td>2012 Demonstrate the viability of CO_2 storage in one new type of geologic formation</td><td>• Analyze Devonian Black Shales in Kentucky for CO_2 storage capacity [University of Kentucky]</td></tr>
</table>

Table 3. Level II - Sequestration Roadmap and Program Plan *(continued)*

	Roadmap			Plan	
	Current Status	R&D Opportunities: Pathway specific	R&D Opportunities: Crosscut	Pathway-level Program Goals	Supporting Program R&D Projects
Enhanced terrestrial uptake	Currently terrestrial uptake offsets roughly one third of global anthropogenic CO_2 emissions. The uptake from domestic terrestrial ecosystems is expected to decrease 13% over the next 20 years as northeastern forests mature. Opportunities for enhanced terrestrial include 1.5 MM acres of land damaged by past mining practices, 32 MM acres of CRP farmland, and 120 MM acres of pastureland.	• Forestation and reforestation • Agricultural practices to increase soil carbon • Integration of fossil energy production and use with land reclamation and productivity improvement	Understand ecosystem level interactions between biosphere and , geologic reservoirs. Determine role of oceans in global ecosystem dynamics.	**2007** Reclaim 100,000 acres of damaged land to increase carbon uptake	• Lab-scale assessment of solid waste soil amendment effects on soil carbon, design of pilot test [ORNL, PNNL] • Demonstrate and assess the life-cycle costs of integrating electricity production with enhanced terrestrial carbon sequestration at TVA's 2,558 MW Paradise Station. Demonstration area is 100 acres. [TVA, EPRI] • Demonstrate reforestation and enhanced carbon sequestration on 500 acres mined lands in Kentucky. [UK, USDA Forest Service]
Ocean fertilization	Experimental results and observed surges in phytoplankton growth after dust clouds pass over certain ocean regions indicate that increasing the concentration of iron and other macronutrients in certain ocean waters can greatly increase the growth of phytoplankton and thus CO_2 uptake. Ocean fertilization remains highly controversial because of uncertainty surrounding other changes it may cause.	• Establish the scientific knowledge base needed to understand, assess, and optimize ocean fertilization • Develop effective macronutrient seeding methodologies • Assess long-term CO_2 fate and flux		Improved scientific understanding of this option	
Ocean injection	No pilot or commercial applications. Small-scale experiments have been carried at the MBARI. Also NETL has the capability to simulate deep ocean conditions and has been conducting experiments on CO_2 droplet stability. A conceptual design of infrastructure for CO_2 transport and injection has been completed by MTI.	• Formation of CO_2 hydrates as a stable form of storage • CO_2 plume dynamics • Environmental impacts of increased CO_2 concentrations in deep ocean water		Improved scientific understanding of this option	• Synthesize CO_2/H_2O hydrates and observe small quantities on the floor of the Monterey Bay [LLNL, NRL, MBARI] • Study CO_2 droplet behavior in simulated deep ocean environments [CSSFA]

<table>
<tr><th colspan="7">Table 4. Level II – MM&V Roadmap and Program Plan</th></tr>
<tr><th colspan="4">Roadmap</th><th colspan="2">Plan</th></tr>
<tr><th rowspan="2"></th><th rowspan="2">Current Status</th><th colspan="2">R&D Opportunities</th><th rowspan="2">Pathway-level Goals</th><th rowspan="2">Supporting Program R&D Projects</th></tr>
<tr><th>Pathway Specific</th><th>Cross cut</th></tr>
<tr><td>Terrestrial Ecosystems</td><td>Roughly 8 mmt of carbon sequestered in terrestrial ecosystems was traded in 2002, requiring preliminary estimations of baseline carbon stocks and projected storage. Current on-the-ground measurements are accurate within plus or minus 5-30% and can cost as little as $1/ton carbon offset.</td><td>• Reduce cost of baselining
• Remote sensing of above ground carbon
• In-field technology for soil carbon measurement
• Correlations between soil and above ground carbon
• Technologies for measuring inorganic soil carbon</td><td rowspan="3">Universal MM&V standards for diverse sequestration systems

Develop protocols for using advanced MM&V technologies in commercial applications

Understand regulatory analogs for geologic and ocean carbon storage

Assess the degree to which risk is inhibiting market use of sequestration for GHG emissions abatement</td><td rowspan="2">2004 Improved accuracy of baseline and inventory MMV technology to enable verifiable credits and carbon accounting

2007 Capability to ensure permanence and protection of human and ecosystem health

2012 MMV represents no more than 10% of total sequestration cost</td><td>• Use aerial videography to construct geo-referenced mosaics and 3D terrain. [Nature Conservancy]
• Develop advanced laser-induced breakdown spectroscopy device for infield detection of soil carbon [LANL]
• Develop capability to use genetic diversity analyses as an indicator of soil carbon accumulation [LANL]</td></tr>
<tr><td>Geologic Formations</td><td>Geophysical techniques can remotely characterize oil reservoir properties and changes post CO_2 injection.
In July 2002, Ontario Power Generation bought 6 million tons of CO_2 emissions credits from Blue Source LLC which provided the emission reductions from oilfield carbon sequestration projects in Texas, Wyoming and Mississippi.
Advanced technologies for higher resolution CO_2 detection are being tested at several sites including the Sliepner, Weyburn, and West Pearl Queen, and Lost Hills reservoirs.</td><td>• Surface to borehole seismic
• Micro-seismic
• Cross well electromagnetic
• Electrical resistance tomography
• CO_2 tracers</td><td>• Design and assess advanced CO_2 imaging technology [LBNL]
• Inject 3,000 tons of CO_2 into the West Pear Queen Oil reservoir and measure CO2 migration [SNL, LLNL]
• Measure and study the movement of CO_2 at the commercial EOR operation in Weyburn, Canada [Dakota Gasification]
• Field test CO_2 tracer chemicals at injections sites in New Mexico and California [CSSFA, LBNL]
• Study natural CO_2 deposits in the United States to evaluate safety and permanence of CO_2 storage [ARI]</td></tr>
<tr><td>Oceans</td><td>Established protocols for measuring dissolved organic and inorganic carbon in ocean water have been developed as a part of varied studies of ocean ecosystems.</td><td>• Capability to image hydrate formation
• Advanced tools for monitoring seawater chemistry and biological impacts in-situ
• Diffraction
• NMR spectroscopy
• Raman spectroscopy</td><td>2007 Develop systems to measure carbon storage and human and ecosystem health impacts for ocean sequestration experiments</td><td>• Sea floor gravity survey of the Sliepner field to monitor CO_2 migration [UCSD]</td></tr>
</table>

Table 5. Major New Initiatives

Initiative	Description	Applicable Technology Development Areas	Metrics for Success 2004	Metrics for Success 2007	Metrics for Success 2012
Collaboration with the National Academies of Science	In 2003 NAS conducted an experts' workshop to identify R&D opportunities in the area breakthrough concepts. The program will use the results from the workshop in crafting a solicitation for R&D projects. Once proposals are received, an NAS committee will evaluate the scientific, technical, engineering and environmental merits of each.	• Breakthrough Concepts	Award multiple promising R&D projects that represent fundamentally new areas for the carbon sequestration program	2 breakthrough direct capture projects show potential for a 10% increase in energy based on lab-scale results	• 1 concept with enough promise to play a role in the 2012 GCCI technology assessment
Regional Sequestration Partnerships	Partnerships will evaluate options and potential opportunities for CO_2 capture, transport, and storage in the defined region and investigate monitoring and verification requirements and regulatory, environmental, and outreach issues.	• Capture • Sequestration • MM&V • Education and Outreach	4-10 cost-shared projects up and running	Phase II awards for technology validation	• Deployment of 1-3 commercial scale carbon sequestration systems that were initiated as a result of regional partnership activities
FutureGen Integrated Sequestration and Hydrogen Research Initiative	Contingent upon funding approval, in FY 2003 the Program plans to release a solicitation for an Integrated Sequestration and Hydrogen Research Initiative in which CO_2 is separated and captured from coal-fired power plant and subsequently sequestered in a geologic formation. The project will focus on large systems, greater that one million tons of CO_2 sequestered per year, and concepts where CO_2 capture and geologic sequestration are integrated.	• Capture • Sequestration • MM&V	Several industry teams rigorously evaluate sequestration options and submit a proposal DOE makes one or more awards for design phase	Demonstration project(s) advance to construction phase	• Demonstrate advanced CO_2 capture technology at large scale • Develop best field practices for geologic CO_2 sequestration • Provide an opportunity to test and refine MMV systems
MM&V Program	Nexus of MMV efforts will contribute to the growing emphasis on MMV consistent with the GCCI. Focus on surface measurement and leak detection. Both the Regional Partnerships and Integrated Demonstration Program have strong MMV aspects.	• Cross cuts all areas		Tools developed enable measurement and verification at reduced cost and improved accuracy	• Internationally accepted protocols

RESOURCE REQUIREMENTS

Figure 6 shows the estimated resources needed to pursue the opportunities identified in the technology roadmap and achieve the program goals. The base program funding is estimated at roughly $50 MM per year, with slightly more between 2006 and 2010. The regional partnerships will require an initial investment but are structured to become self-sustaining after five years. The FutureGen Integrated Sequestration and Hydrogen Research Initiative will require a significant investment. This is due to the fact that large deployments are needed to prove out new technologies and that a portfolio of projects are needed to validate the different types of CO_2 point sources and storage options.

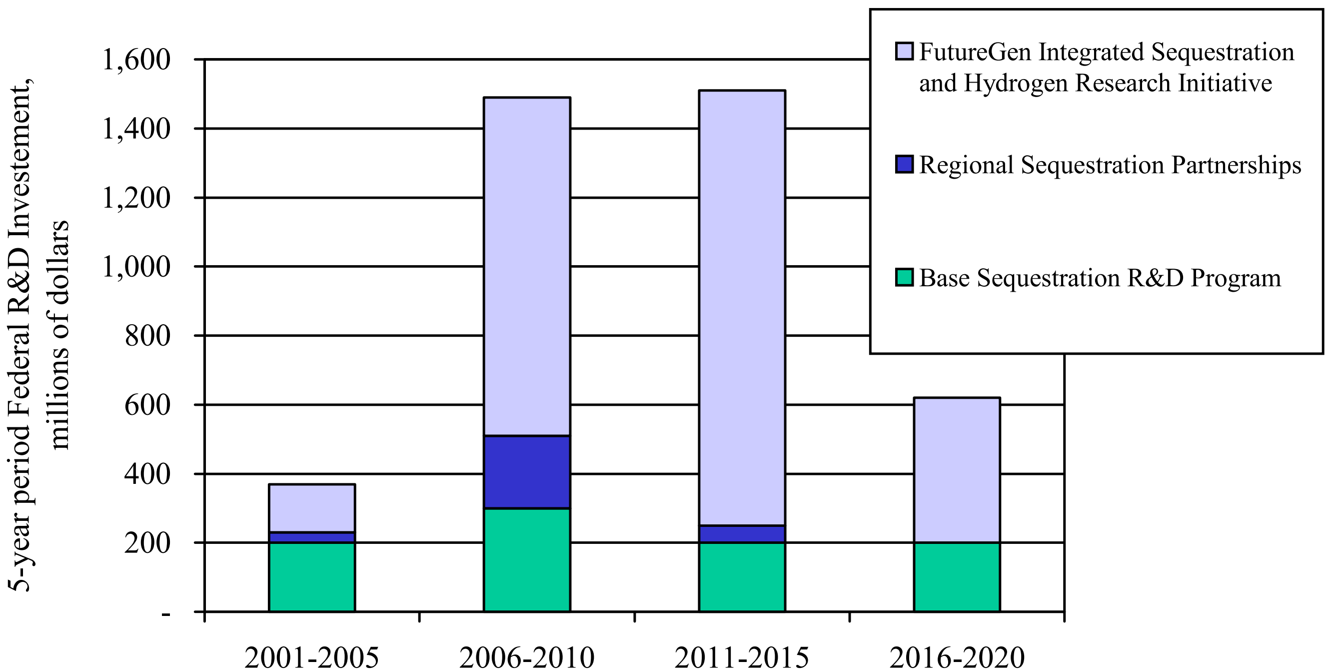


Figure 6. Funding Requirements of the Carbon Sequestration Program

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U.S. DOE Integrated Collaborative Technology Development Program for CO_2

Scott M. Klara and
Rameshwar D. Srivastava

U.S. DOE Integrated Collaborative Technology Development Program for CO_2 Separation and Capture

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Electric power generation represents one of the largest carbon dioxide (CO_2) emitters in the United States. Roughly one-third of all the United States' carbon emissions come from power plants. Since electricity generation is expected to grow, and fossil fuels will continue to be the dominant fuel source, power generation can be expected to provide even greater CO_2 contributions in the future. Consequently, an important component of the United States Department of Energy's (DOE's) research and development program is dedicated to reducing CO_2 emissions from power plants by developing technologies to capture CO_2 for utilization and/or sequestration. A primary goal of this research is to develop technology options that dramatically lower the cost of eliminating CO_2 from flue gas and other streams by use of either pre- or post-combustion processes. This research is in its early stages, and is exploring a wide range of approaches, including membranes, improved CO_2 sorbents, advanced scrubbing, oxyfuel combustors, formation of CO_2 hydrates, and economic assessments. This paper presents an overview of the DOE research program in the area of CO_2 separation and capture, while specifically addressing the status of research efforts related to promising pathways and potential technological breakthroughs.

INTRODUCTION

Fossil fuels currently supply over 85% of the energy needs of the U.S., and their combustion is responsible for about 90% of the greenhouse gas (GHG) emissions in the U.S. [1]. Use of these fuels, domestically and internationally, is expected to increase well into the 21st century. The Energy Information Administration within the U.S. Department of Energy (DOE) projects U.S. consumption of coal, oil, and natural gas to increase by 40%, and carbon emissions to rise by 33% over the next 20 years (See Figure 1).

Carbon sequestration holds great potential to reduce GHG emissions at costs and impacts that are economically and environmentally acceptable. The DOE's Office of Fossil Energy's (FE) formal carbon sequestration effort began in 1997.

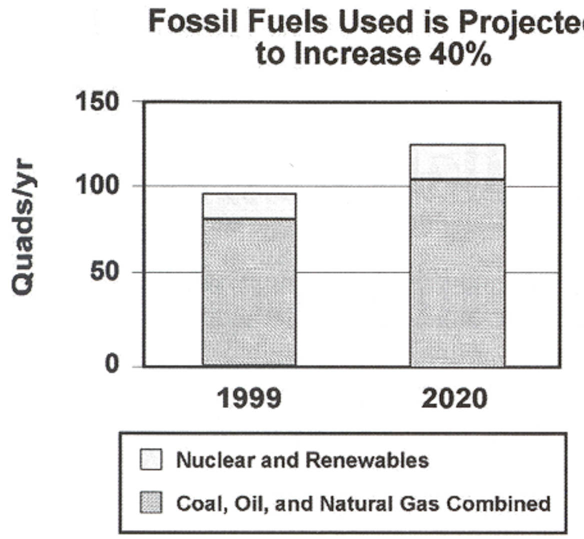
The Carbon Sequestration Program is pursuing five technology pathways to reduce GHG emissions:

- Separation and capture
- Geologic sequestration
- Terrestrial sequestration
- Oceanic sequestration
- Novel sequestration systems

These five pathways encompass a broad set of opportunities for both technology development and partnership formation for national and international cooperation. This paper deals mainly with the first of these pathways, namely separation and capture.

In addition to CO_2, methane (CH_4) and nitrous oxide (N_2O) are other major anthropogenic emissions that contribute to global climate change. On a pound for pound basis, both CH_4 and N_2O are more potent GHGs than CO_2. However, in terms of the quantity emitted, CO_2 far outstrips other GHGs and is, thus, the primary focus of mitigation efforts. Efforts to decrease non-CO_2 GHG emissions are included in the Sequestration Program, but are not discussed in this paper.

An important component of DOE's Carbon Sequestration program is directed toward reducing CO_2 emissions from power plants. Roughly one-third of the United States' anthropogenic CO_2 emissions come from power plants (See Figure 2). CO_2 emissions in the U.S. from electricity generation by fossil-fuel burning power plants increased by 23.5% between 1990 and 2000 [2]. Moreover, most power plants use air for combustion, which means that the major constituent of the flue gas is nitrogen. This makes it difficult and expensive to capture CO_2 as a concentrated stream, which is required for most storage, conversion, and reuse applications. One way of mitigating GHG emissions in a safe and environmentally-friendly manner is to capture CO_2 and store it in geological formations.



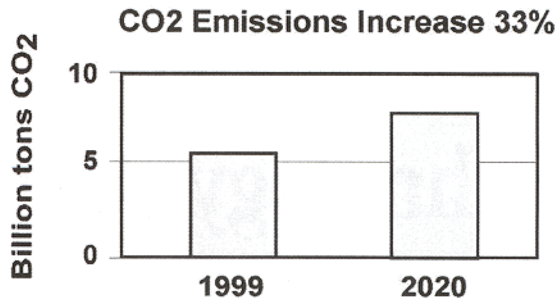


Figure 1. U.S. energy consumption and GHG emissions in 2020.

This has emerged as one of the most promising options for sequestering CO_2 from energy plants [3].

Carbon sequestration is an underexplored area of science and technology. In order for recovery/sequestration to work, improved CO_2 capture technologies are needed, and costs must be reduced substantially. Capture technology, based on the use of physical or chemical sorbents, such as amines, is in wide use today to remove CO_2 from natural gas, which can be used in the food industry and for tertiary recovery in oil fields. However, the cost is on the order of \$50 per ton of CO_2 removed, or about 5 cents per kWh, too high for cost-effective GHG emissions reductions. Additionally, existing capture systems use substantial amounts of energy, reducing a power plant's net generation capacity, sometimes by as much as 30%. DOE's long-term goal is to achieve sequestration with only a modest increase in energy costs [4, 5]. The programmatic timeline is to demonstrate, at commercial scale, a portfolio of safe and cost-effective GHG capture, storage, and mitigation technologies by 2012.

CARBON SEQUESTRATION RESEARCH AND DEVELOPMENT PROGRAM

Before it can be sequestered, CO_2 must first be separated and captured. Therefore, the Carbon Sequestration Research and Development Program is exploring a portfolio of new and improved technologies to reduce the capital cost and energy penalty for CO_2 capture. During the FY2000 to FY2002 period, the DOE Carbon Sequestration Program issued a solicitation and selected 20 R&D projects in the areas of CO_2 capture and storage in geologic formations. These programs have up to a 40% non-DOE cost share. This research is in its early stages and is exploring a wide range of capture approaches, including membranes, improved CO_2 sorbents, advanced combustor concepts, advanced scrubbing, formation of CO_2 hydrates, and economic assessments. DOE is also a partner in the CO_2 Capture Project (CCP) with an international team of energy companies to develop a set of new technologies to reduce the cost of capturing CO_2 from fossil fuel combustion.

There are two general approaches to CO_2 capture: precombustion decarbonization and post-combustion capture. Either the carbon can be removed before the fuel is burned, or CO_2 can be recovered from the flue gas. In addition, the use of pure oxygen, rather than air, in combustion, known as oxyfuel combustion, has a high potential for reducing CO_2 separation and capture costs.

PRECOMBUSTION DECARBONIZATION

Precombustion decarbonization involves removal of carbon from a gaseous, liquid, or solid fuel before it is burned. Various approaches are possible. A very promising technology involves gasifying coal and then scrubbing the CO_2 from the fuel gas before combustion. The CO_2 is normally removed by a chemical or physical absorption system. Existing capture technologies operate at a low temperature, requiring the syngas produced in the gasifier to be cooled for CO_2 capture and then reheated before combustion in a turbine. Substantial cost reductions in CO_2 capture and separation are expected to come through integrated designs incorporating the use of membranes and other breakthrough recovery technologies.

CO_2 Selective Ceramic Membrane to Improve the Water-Gas Shift Reaction

This technology involves precombustion decarbonization with the addition of an innovative water-gas shift (WGS) reactor to increase the amount of CO_2 captured. The WGS reactor consists of ceramic tubes that incorporate a membrane permeable to CO_2, but not to other gases. The tubes are filled with catalyst. As the fuel gas from the coal gasifier passes through the WGS reactor, the CO_2 produced by the reaction, as shown in Equation 1, diffuses through the membrane, allowing the reaction to approach completion.

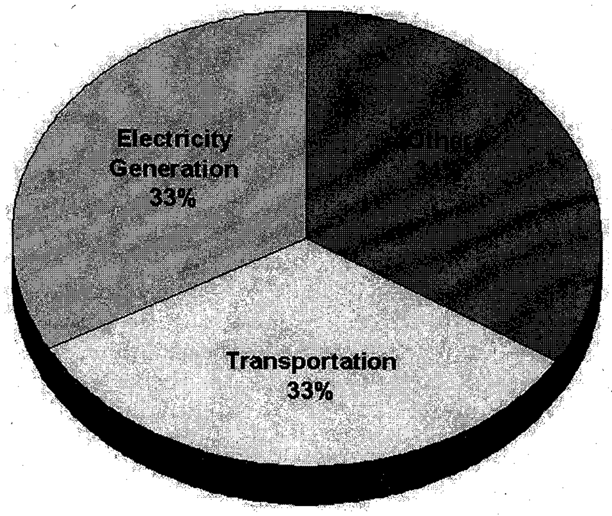


Figure 2. U.S. carbon emissions sources.

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (1)$$

This produces a hydrogen-rich fuel stream, while simultaneously producing a pure CO_2 stream for use or sequestration. The hydrogen can be sent to a fuel cell or burned in a combustion turbine. In either case, the only product is water, which is innocuous to the environment. This project is being conducted by Media and Process Technology, Inc., in partnership with the University of Southern California. They have developed a technique for depositing hydrotalcite in the pores of a ceramic substrate. The hydrotalcite is permeable to CO_2, but plugs the pores, preventing passage of other gases. The project team is currently working on improving production procedures and determining operating conditions to maximize CO_2 permeance.

POST-COMBUSTION CO_2 CAPTURE

Post-combustion capture involves the removal of CO_2 from the flue gas produced by fuel combustion. The major problem with this approach is that flue gas is usually at near atmospheric pressure, and the CO_2 concentration is low. The resulting low partial pressure of CO_2 results in only a small driving force for traditional adsorption/absorption processes. While post-combustion CO_2 capture may not have the greatest potential for step-change reductions in separation and capture costs, it has the greatest near-term potential for reducing emissions, since post-combustion processes can be retrofitted to existing facilities. Although the processes discussed below can be used to remove CO_2 from flue gas, the benefits of these developments will be equally applicable to the removal of carbon dioxide from gasifier product streams for the production of syngas or pure hydrogen.

Electric Swing Adsorption

Electric Swing Adsorption (ESA) is an advanced separation system for CO_2 removal from syngas being developed for use with the gasification of low hydrogen-to-carbon ratio fuels, such as petroleum coke. Oak Ridge National Laboratory has developed a novel process, which adsorbs CO_2 on a carbon substrate. After saturation of the carbon fiber adsorbent with CO_2, immediate desorption of the adsorbed gas is accomplished by applying low voltage across the adsorbent. This technology is being developed to remove CO_2 from the exhaust gas of a conventional turbine combined with a non-condensing steam turbine. Calculations based on available adsorption data indicate that it should be possible to develop an improved CO_2-separation process compared to existing technology.

Stable High Temperature Polymer Membranes

Many membrane systems used for industrial gas separation applications employ polymer membranes. Such applications include the production of high-purity nitrogen, dehydration and removal of acid gases from natural gas, and recovery of hydrogen from process streams. However, many gas separation applications require materials that are stable at high temperatures and pressures. Polymeric materials currently used commercially have thermal and mechanical limits too low for such applications. Consequently, there is a compelling need for membrane materials that can operate under more extreme conditions for extended periods of time while providing an acceptable level of performance.

Los Alamos National Laboratory is developing a high-temperature polymeric membrane with better separation performance by supporting a polybenzimidazole (PBI) film on a sintered metal support. PBI possesses excellent chemical resistance, a high glass transition temperature (450° C), and good mechanical strength. Tests for H_2, CO_2, CH_4, and N_2 permeability with the membrane oriented with the polymeric layer on the feed side have shown promising results. This type of membrane is highly selective and able to operate at flue gas conditions.

Advanced Gas/Liquid Scrubbing

A major problem associated with chemical absorption using amines is the degradation of the solvent through irreversible side reactions with SO_2 and other flue gas components. Such reactions lead to numerous problems, such as foaming, fouling, increased viscosity, and formation of stable salts in the amine. Amine degradation results in solvent loss, requiring a replacement rate of up to eight pounds of amine per ton of CO_2 captured. A focus of R&D activities at the National Energy Technology Laboratory (NETL) is a study of amine degradation under actual plant conditions.

This study will lead to a better understanding of the chemistry of solvent degradation, which is known to increase corrosion. Understanding this phenomenon will improve operations and decrease costs, since to reduce corrosion, solvent strength is kept relatively low, resulting in large equipment sizes and high regeneration energy requirements. In addition, several researchers have shown that blending amines increases the absorption rate. The work at the University of Texas at Austin focuses on expanding the investigation of promoted potassium carbonate using piperazine as the amine.

Regenerable CO_2 Sorbent Development

A different approach for CO_2 capture employs dry scrubbing—a process that involves chemical adsorption with a dry sorbent. Such a sorbent can remove the pollutant, be regenerated to produce a concentrated stream of CO_2, and be recycled. This process can have economic advantages compared to commercially available wet scrubbing amine processes.

Research Triangle Institute has initiated development of a process that uses a regenerable, sodium-based sorbent for CO_2 recovery. Preliminary microreactor tests with sodium carbonate have indicated that absorbing CO_2 and steam to form bicarbonate, with subsequent regeneration to the carbonate, is a viable process. Because sorbent regeneration uses waste heat, the power requirement for capture of CO_2 is relatively small. Various system configurations are being simulated to define optimal heat management.

NETL has pioneered research to identify regenerable sorbents that can be used for CO_2 capture. The active component in a calcium-based sorbent being studied chemically bonds with CO_2 and is later regenerated using heat or a reducing agent. Packed bed testing is now in the planning stage. In another project, CO_2 is absorbed by a zeolite based sorbent, and a temperature/pressure swing is performed to recover the carbon dioxide. The project team (NETL and Carnegie-Mellon University) is currently working on simulation modeling to understand the performance of high-temperature sorbents and on high-pressure reactor testing of promising synthetic zeolites.

OXYFUEL TECHNOLOGY

Oxygen-Fired Combustion for CO_2 Capture

The objective of oxygen-fired combustion is to burn the fuel in enriched air or pure oxygen to produce a concentrated stream of CO_2. Oxygen-fired combustion presents significant challenges, but also provides a high potential for a technological breakthrough and a step-change reduction in CO_2 separation and capture costs. The barriers and issues include:

- Oxygen from cryogenic air separation is expensive and, because in oxygen-fired combustion, all the carbon in the fuel is converted to CO_2 using pure oxygen, rather than only part of the carbon with gasification, oxygen combustion consumes several times more oxygen than coal gasification followed by combustion of the syngas in air.
- Combustion of fuels in pure oxygen occurs at a temperature too high for existing boiler or turbine materials, while CO_2 recycle to control temperature increases the parasitic power load.

Development and costing of an optimized oxygen-fired combustion scheme requires an engineering study to identify and resolve the technical issues related to application of oxygen firing with flue gas recycle to the boiler and process heaters. Alstom Power has outlined an approach in which two sets of economic evaluations would analyze a fossil fuel-based (coal and petroleum coke) circulating fluidized bed (CFB) combustor, and a biomass-based CFB for power production. The first step is to identify and analyze normal baseline conditions for CFB combustion with air firing both without CO_2 capture and with a novel high-temperature CO_2 capture and sorbent regeneration process. Next, CFB-based power plants employing an oxygen/recycled flue gas mixture as the oxidizing agent will be studied to determine what operating conditions and gas cleanup processes are most economical. The CO_2 concentration in the flue gas can be greatly increased by using oxygen instead of air for combustion. Flue gas is recycled to moderate the combustion temperature.

Comparisons will also be made with Integrated Gasification Combined Cycle (IGCC) cases that have already been evaluated by Parsons Energy and Chemical Group. In this way, important features that can improve plant operations by utilizing oxygen firing will be explored, identified, and included in plant designs.

Integration of Membrane Air Separation

The economics of both oxygen-firing and IGCC can be improved by the application of advanced oxygen production technology. New air separation processes using high temperature oxygen ion transport ceramic membranes are being developed by several consortia. For oxygen-fired combustion applications, integration of an oxygen transport membrane (OTM) for oxygen production with the combustion system can provide a method for the cost-effective capture of CO_2 from power plants. Praxair, in conjunction with Alstom Power, has initiated the development of a novel technology that integrates a high-temperature OTM with boiler components to enhance both oxygen production and boiler efficiency (See Figure 3).

OTM membranes are based, in part, on Praxair-patented materials that have demonstrated ability for rapid electron conduction. A condensing heat exchanger will be used to take advantage of the high water content in the flue gas from combustion with pure oxygen. A high driving force across the ceramic membrane, due to pressurized air, and the high temperature environment inherent in combustion, result in a significant reduction in the power consumption for oxygen production. The resultant combustion process will not only lead to low NO_x and CO emissions, but also increase the CO_2 concentration in the flue gas sent to the capture system, thus leading to lower capital costs. The technical challenge is to develop materials with enhanced conductivity and stability, and to produce ceramic structures specifically suited to combustion applications.

NOVEL CONCEPTS

Carbon Dioxide Separation Using Hydrates

An entirely new concept for recovering CO_2 from process streams is the formation of hydrates, ice-like

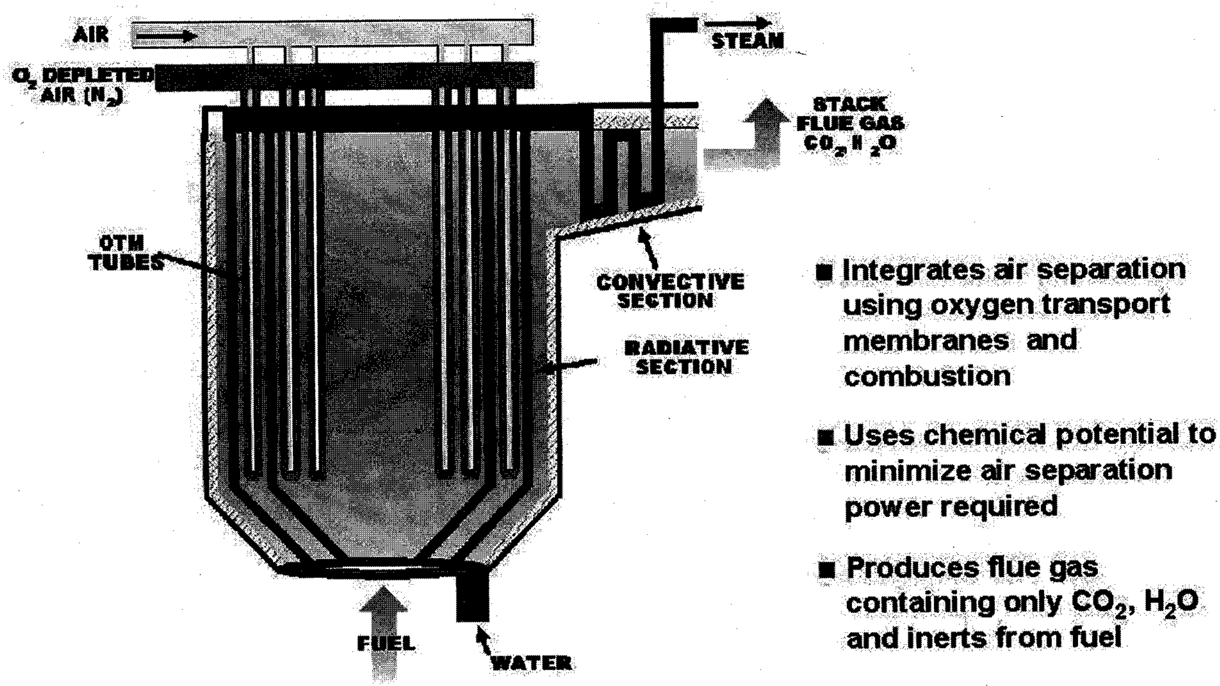


Figure 3. Praxair advanced boiler.

complexes of water and CO_2 molecules. Many people are familiar with methane hydrates, in which a methane molecule is enclosed in a cage of water molecules, but are unaware that CO_2 can form similar hydrates under suitable conditions. The California Institute of Technology has developed a bench-scale apparatus to produce CO_2 hydrates. The objective of the current project team (Los Alamos National Laboratory, Nextant, Inc., and SIMTECHE) is to develop this concept into the basis for a commercial process that removes CO_2 from flue gas by contacting it with water at low temperature (0° C) and high pressure (1-7 MPa) to form crystalline ice-like solids that can be removed from the system.

A new test unit has been constructed for experimentation. Figure 4 is a schematic of a CO_2 hydrate separation process operating on a synthesis gas stream that has undergone the WGS reaction. Water and CO_2 in a greater than 12/1 molar ratio flow through a venturi to achieve intimate contact, and then into a cooler to remove the heat of formation of the hydrate. The slurry and unreacted gas then flow to a separator. Work to date has demonstrated that hydrates can be formed in systems with very short residence times, and that continuous operation is possible, provided operating conditions are adjusted so that plugging does not occur.

The next step in the development process is the design, construction, and operation of a pilot plant. However, further data are needed before this can be done, including the physical properties of the hydrate slurry, practical ranges of the key process variables, and tests with $CO_2/H_2/H_2S$ mixtures. Using CO_2 hydrates to purify gas streams is a potentially less energy-intensive recovery method. It is also possible that CO_2 hydrate slurries could be pumped to sequestration sites without regeneration. Implementation of this technology will be best suited to gasification systems that operate at pressures higher than those of typical flue gas streams.

Chemical Looping

Indirect combustion of coal, sometimes referred to as chemical looping, will be evaluated by Alstom Power. In chemical looping, oxygen for combustion is provided by a metal oxide, rather than by air. Fuel gas (CO plus H_2) produced by the gasification of coal reduces a solid transition metal oxide in a fluidized bed reactor to a lower oxidation state, producing water and CO_2. The off-gas stream is cooled to condense water and produce a pure CO_2 stream for sequestration. The reduced metal containing solid is transferred to a second fluidized bed reactor, where it is reoxidized with air. This exothermic reaction heats the oxygen-depleted air, which is sent to power production.

OTHER ACTIVITIES

Modeling/Assessment

There is a need to develop a comprehensive economic model that that will enable different options for CO_2 capture from power plants to be systematically evaluated, including pipeline costs. Carnegie Mellon University is developing such a model. The initial focus includes current commercial technologies, such as amine-based CO_2 capture, shift conversion, pipelines, and geologic storage. The model is expected to be capable of establishing a common

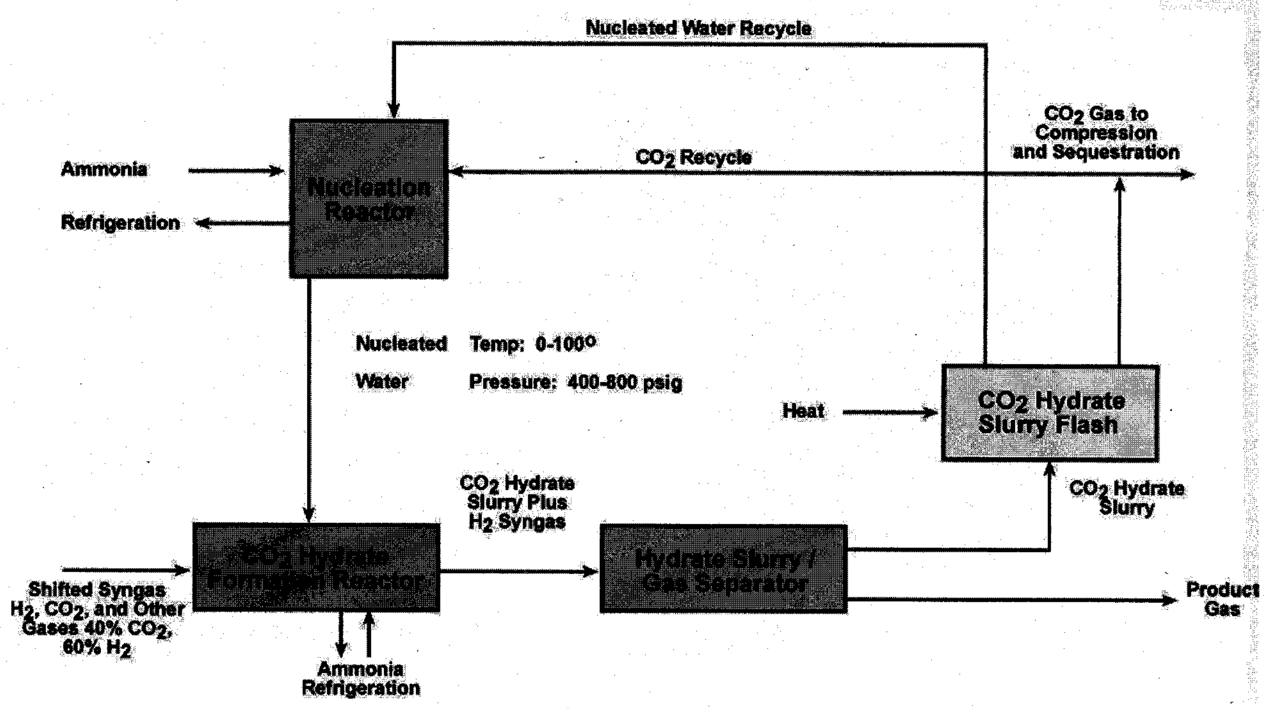


Figure 4. Conceptual process block flow diagram of a CO_2 hydrate process.

set of performance metrics and evaluating the overall cost of CO_2 sequestration, including the component costs of new separation and capture modules, transportation and sequestration in geologic reservoirs and unmineable coal seams, and use in enhanced oil recovery.

NETL and Science Applications International Corporation are developing a computer model-based technique for evaluating CO_2 recovery and sequestration technologies. With existing studies as a baseline, all technologies in the DOE portfolio will be evaluated to continually assess their potential technical and economic performance. This will ensure that the highest potential projects are kept at the forefront of the DOE development effort.

CO_2 Capture Project

To further enhance the effort to reduce GHG emissions, DOE is sponsoring the CO_2 Capture Project (CCP) with an international team of energy companies lead by BP, and including Chevron-Texaco, ENI (Italy), Shell, Norsk Hydro (Norway), PanCanadian (Canada), Statoil (Norway), and Suncor Energy (Canada). This joint industry project will demonstrate the feasibility of capturing the CO_2 produced from burning a variety of fuel types and storing it in unmineable coal seams and saline aquifers.

The CCP has issued contracts with technology developers in the U.S., the European Union, and Norway to carry out studies in various process areas, including geologic storage, post-combustion CO_2 separation and capture, precombustion decarbonization, and fuel combustion with pure oxygen [6]. The potential exists for many scientific breakthroughs from this project, such as the development and evaluation of a combined shift reaction and CO_2 separation system employing high temperature adsorbents. This process would selectively remove CO_2 from a reacting gas mixture, thereby increasing conversion and providing two gas streams requiring minimal further purification. Technology developed by Air Products and Chemicals involves the precombustion decarbonization of a hydrocarbon feedstock that has been gasified by reaction with steam and/or oxygen to produce a $H_2/CO_2/H_2O/CO$ gas mixture with trace contaminants. This concept has already been demonstrated at laboratory scale. Development needs are to apply the system to CO_2 capture and optimize the adsorbent and cycle for large-scale use.

Four membranes have been identified to achieve the CO_2 recovery target at a concentration above 97 mol %. Each of these membranes (Cu-Pd, supported zeolite, silica, and electro-ceramic) will be developed and characterized. For example, ECN Dutch Energy Efficiency Institute will develop silica membranes and provide mathematical models. Fluor Daniels will develop simulations of the overall process incorporating a model of the membrane reactor supplied by ECN.

Other potential scientific breakthroughs that could result from the CCP include:

- New solvents and/or contactors to reduce the cost of CO_2 separation.
- An emerging H_2 generation process integrated with CO_2 capture.
- Understanding the production of fuel-grade H_2 and its combustion properties.

- An enhanced understanding of controls and requirements for geologically sequestering CO_2.

Information on capture and sequestration options generated during the performance of these parallel and complimentary studies will maximize technology transfer and, hence, benefit CO_2 reduction efforts in the U.S and globally.

CONCLUSIONS

The DOE Carbon Sequestration Program is developing a portfolio of technologies that hold great potential to reduce GHG emissions. The programmatic timeline is to demonstrate a series of safe and cost effective GHG capture, storage and mitigation technologies at the commercial scale by 2012, with deployment leading to substantial market penetration beyond 2012. Developments are directed toward substantial improvements in performance and cost reduction compared to state-of-the-art alternatives. Wide deployment of these technologies holds great promise to slow the growth of GHG emissions in the near-term, while ultimately leading to stabilized emissions towards the middle of the 21st century.

This paper has presented a brief overview of the DOE Carbon Sequestration Program. More details on these and other R&D projects in the portfolio can be found at the referenced Web site [5].

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Integrated collaborative technology development program for CO_2 sequestration in geologic formations—United States Department of Energy R&D

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Abstract

A major contributor to increased atmospheric CO_2 levels is fossil fuel combustion. Roughly one third of the carbon emissions in the United States comes from power plants. Since electric generation is expected to grow and fossil fuels will continue to be the dominant fuel source, there is growing recognition that the energy industry can be part of the solution to reducing greenhouse gas emissions by capturing and permanently sequestering CO_2. Consequently, an important component of the United States Department of Energy's (DOE) research and development program is dedicated to reducing CO_2 emissions from power plants by developing technologies for capturing CO_2 and for subsequent utilization and/or sequestration.

Injection of CO_2 into geologic formations is being practiced today by the petroleum industry for enhanced oil recovery, but it is not yet possible to predict with confidence storage volumes, formation integrity and permanence over long time periods. Many important issues dealing with geologic storage, monitoring and verification of fluids (including CO_2) in underground oil and gas reservoirs, coal beds and saline formations must be addressed. Field demonstrations are needed to confirm practical considerations, such as economics, safety, stability, permanence and public acceptance.

This paper presents an overview of DOE's research program in the area of CO_2 sequestration and storage in geologic formations and specifically addresses the status of new knowledge, improved tools and enhanced technology for cost optimization, monitoring, modeling and capacity estimation. This paper also highlights those fundamental and applied studies, including field tests, sponsored by DOE that are measuring the degree to which CO_2 can be injected and remain safely and permanently sequestered in geologic formations while concurrently assuring no adverse long term ecological impacts.

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1. Introduction

Predictions of global energy use in this century suggest a continued increase in carbon emissions and rising concentrations of CO_2 in the atmosphere. A major contributor to increased greenhouse gas (GHG) emission levels is fossil fuel combustion. Roughly one third of the carbon emissions in the United States comes from power plants. Since electric generation is expected to grow and fossil fuels will continue to be the dominant fuel source, there is growing recognition that the energy industry can be part of the solution to reducing GHG emissions by capturing and permanently sequestering CO_2. Carbon sequestration holds great potential to reduce GHG emissions at costs and impacts that are economically and environmentally acceptable. The year 1997 represents the start of DOE's Office of Fossil Energy's (FE) formal Carbon Sequestration Program. The objective of the Carbon Sequestration Program is to provide long range options for drastically reducing CO_2 emissions from fossil fuel fired heat and power facilities [1,2].

The Carbon Sequestration Program is pursuing five technology pathways to reduce GHG emissions:

- Separation and Capture targets novel, low cost approaches for capture of carbon or CO_2 from energy production and conversion systems.
- Geologic Sequestration assesses the applicability and effectiveness of long term CO_2 storage in geological structures, such as oil and gas reservoirs, unmineable coal seams and deep saline aquifers.
- Terrestrial Sequestration examines the potential to enhance terrestrial uptake and retention of atmospheric CO_2 by coupling improved agricultural and forestry practices with fossil energy production and use systems.
- Oceanic Sequestration examines potential mechanisms for enhancing ocean uptake of atmospheric CO_2 or for deep ocean storage of liquid CO_2.
- Novel Sequestration Systems examines novel approaches to chemical, biological or other processes to recycle or reuse CO_2 produced by energy systems.

These five pathways encompass a broad set of opportunities for both technology development and partnership formation for national and international cooperation. A paper discussing the first of these pathways, separation and capture, was recently published [3]. This paper deals mainly with the second of these pathways, geologic sequestration. Summaries of technology developments emerging from the Carbon Sequestration Program are presented.

2. Sequestration of carbon dioxide in geologic formations

Geologic CO_2 sequestration involves the injection of CO_2 into geologic formations, the most important of which are deep coal seams, saline aquifers and depleted oil and gas reservoirs. The

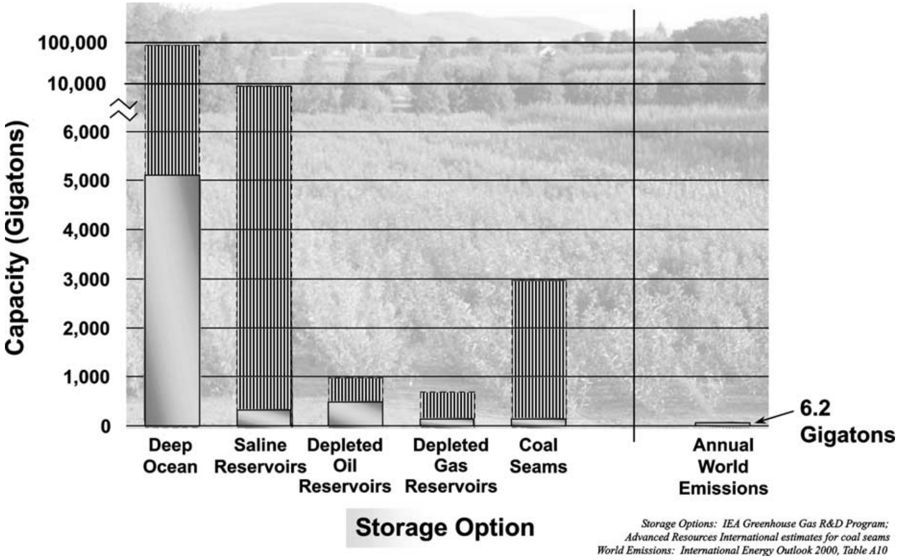

Fig. 1. Large potential worldwide storage capacity.

estimated capacity of geologic formations (see Fig. 1) is large enough to store decades worth of emissions. These capacity estimates are likely to be conservative, as the CO_2 sequestration potential of geologic reservoirs depends on many factors that are, as yet, poorly understood. These include reservoir integrity, volume, porosity, permeability and pressure. Because these factors vary widely, even within the same reservoir, it can be difficult to establish a reservoir's storage potential with certainty.

Injection of CO_2 into geologic formations is being practiced today by the petroleum industry for enhanced oil recovery (EOR), but it is not yet possible to predict with confidence storage volumes, formation integrity and permanence over long time periods. Many important issues dealing with geologic storage, such as interactions between CO_2 and reservoir rock and other fluids and monitoring and verification of fluids (including CO_2) in underground oil and gas reservoirs, coal beds and saline formations, must be addressed.

Large scale field demonstrations are needed to confirm practical considerations, such as economics, safety, stability, permanence and public acceptance. Early tests will involve sequestration experiments in which collateral benefits are likely, such as storing CO_2 in depleted oil and gas reservoirs where additional hydrocarbons may be produced and sequestering CO_2 in coal seams in conjunction with coal bed methane (CBM) production. The main driver, however, is to ensure the safety of, and gain public acceptance for, large scale CO_2 sequestration projects. The purpose of DOE sponsored research in geologic sequestration is to provide answers to the many remaining questions.

The three major research thrusts of the geologic sequestration activity are:

- monitoring and verification;
- health, safety and environmental risk assessment;
- knowledge base and technology for CO_2 storage reservoirs.

3. Monitoring and verification

A critical R&D need is to develop a comprehensive monitoring and modeling capability that not only focuses on technical issues but also can help ensure that geologic sequestration of CO_2 is safe. Long term geologic storage issues, such as leakage of CO_2 through old well bores, faults, seals, or diffusion out of the formation, need to be addressed. Many tools exist or are being developed for monitoring geologic sequestration of CO_2, including well testing and pressure monitoring; tracers and chemical sampling; surface and bore hole seismic; and electromagnetic/ geomechanical meters, such as tiltmeters. However, the spatial and temporal resolution of these methods may not be sufficient for performance confirmation and leak detection. Therefore, further monitoring needs include:

- high resolution mapping techniques for tracking migration of sequestered CO_2;
- deformation and microseismicity monitoring;
- remote sensing for CO_2 leaks and land surface deformation.

Fig. 2 provides an overview of the participants, approach and synergies for monitoring and verification projects within the DOE program. Following are descriptions of major projects aimed at developing effective monitoring tools and technologies, which hold high potential for improving our ability to characterize the location, quantity and condition of sequestered CO_2.

Sandia National Laboratory, Los Alamos National Laboratory, and the National Energy Technology Laboratory have partnered with an independent producer, Strata Production Company, to investigate down hole injection of CO_2 into a depleted oil reservoir, the West Pearl Queen Field, in New Mexico. A comprehensive suite of computer simulations, laboratory tests, field measurements and monitoring efforts will be used to understand, predict and monitor the geomechanical and hydrogeologic processes involved. Injection into this reservoir is planned through an inactive well, while a producing well and two shutoff wells will be used for monitoring. CO_2 migration and surface detection studies will be conducted by combining satellite visible light and infrared views with satellite radar and optical aerial photography. Remote geophysical surveys will attempt to detect and characterize changes in fluid saturation and pressure by observing the seismic response of the reservoir during injection. These observations will be used to calibrate, modify and validate modeling and simulation tools.

Use of new reservoir mapping and predictive tools (surface seismic and tracer injection) to develop a better understanding of the behavior of CO_2 in a geologic formation in conjunction with the Weyburn unit is being addressed by Natural Resources Canada and Dakota Gasification Company. Weyburn Field, in southwestern Saskatchewan, Canada, was discovered in 1954. Starting in 2001, several tons per day of CO_2 are being pumped into this reservoir to produce incremental oil. The CO_2 is being transported by pipeline 330 km from the Great Plains Synfuels Plant in Beulah, North Dakota. It is expected that ≈50% of the CO_2 will remain sequestered with the oil that remains in the ground. The 50% that comes to the surface with the produced oil will come out of solution as the pressure drops and be recycled to the injection wells. This work will examine the way CO_2 moves through the reservoir rocks, the precise quantity that can be stored in a reservoir and how long the CO_2 could be expected to remain trapped in the underground formation.

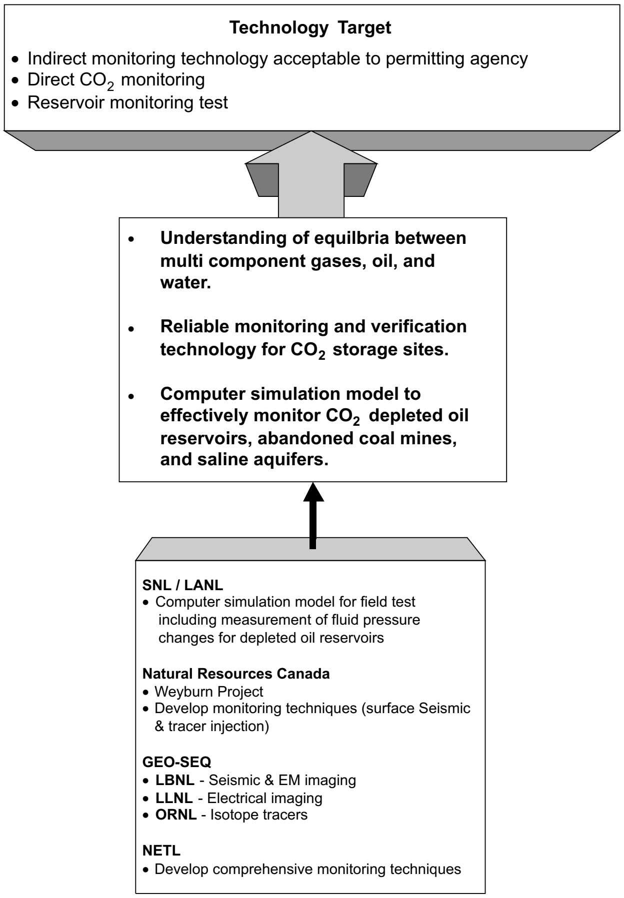

Fig. 2. Monitoring and verification.

Lawrence Berkley, Lawrence Livermore and Oak Ridge National Laboratories and their partners are developing innovative monitoring technologies to track migration of CO_2. Called GEO-SEQ, described later in conjunction with other major activities, the project will develop and use seismic techniques, electrical imaging and isotope tracers for optimizing value added sequestration technologies for brine, oil and gas and coal bed methane formations.

4. Health, safety and environmental risk assessment

Assessing the risks of CO_2 release from geologic storage sites is fundamentally different from assessing risks associated with hazardous materials, for which best practice manuals are often available. Because CO_2 is benign at low concentrations, a new framework for assessment, implementation and regulation will be needed.

Health, safety and environmental risk assessment is a process for identifying adverse health, safety and environmental consequences and their associated probabilities. The assessment of the risks associated with sequestration of CO_2 in geologic formations includes identifying potential subsurface leakage modes, likelihood of an actual leak, leak rate over time and long term implications for safe sequestration. Diagnostic options need to be developed for assessing leakage potential on a quantitative basis. Fig. 3 provides an overview of project participants, their approach, technology targets and the synergies involved in the DOE program.

Advanced Resources International is evaluating the effect of slow or rapid CO_2 leakage on the environment during initial operations or the subsequent storage period. The study will include a comprehensive and multi-disciplinary assessment of the geologic, engineering and safety aspects of natural analogs. Five large natural CO_2 fields, which provide a total 1.5 billion ft^3/day of CO_2 for EOR projects in the United States, have been selected for evaluation [4]. Based on the results of a geochemical analysis of CO_2 impacts and geomechanical modeling, an evaluation of environmental and safety related factors will be made.

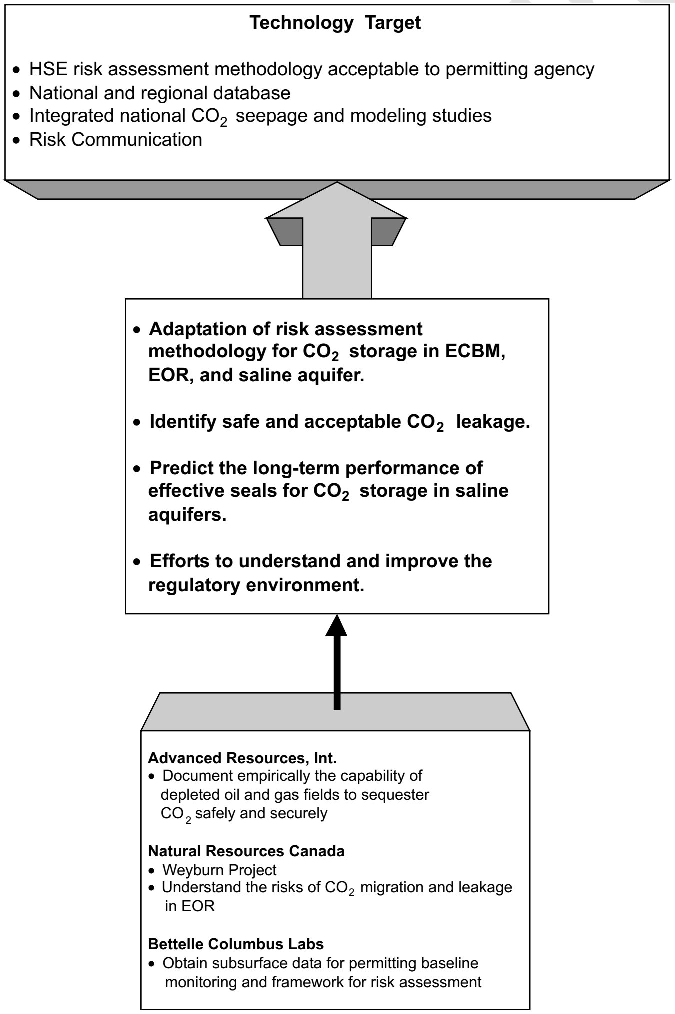

Fig. 3. Health, safety and envirnomental risk assessment.

The Weyburn project will focus on direct injection of CO_2 into a partially depleted carbonate reservoir in the Williston Basin as part of a large scale, commercial EOR operation in Saskatchewan. The miscible CO_2 EOR flood will be monitored from its inception to its conclusion. The study will confirm the ability of an oil reservoir to geologically contain, isolate and permanently store a significant amount of CO_2. It will produce a credible assessment of the permanent containment of injected CO_2, evaluated by long term predictive simulations and formal risk analysis techniques. Such an assessment will help answer questions by regulatory bodies as to the security of large volume CO_2 sequestration/storage, not only in the Williston Basin but also in other areas where geological similarities exist.

Battelle is leading a research team, which includes National Laboratories, academia and the energy industry, to conduct site assessment to develop the baseline information necessary to make decisions about a potential CO_2 geologic sequestration demonstration and verification experiment in a saline aquifer. This project will be focused in the Ohio River Valley area, which is home to the largest concentration of coal based electricity generation in the nation. Tests will be conducted to comprehensively characterize the reservoirs, cap rocks and overlying layers. These and other fundamental issues will be used to develop and apply a comprehensive Risk Analysis and Stakeholder Involvement Process for the transport, injection and long term sequestration of CO_2 at a field demonstration site.

5. Knowledge base and technology for CO_2 storage reservoirsc

The object for this group of projects is to increase the knowledge base and technology options for sequestering CO_2 in geologic formations. Fig. 4 presents a summary of projects being sponsored by the DOE program in the area.

6. Sequestration in deep coal seams

An attractive option for disposal of CO_2 is sequestration in deep, unmineable coal seams [5]. Not only do these formations have high potential for adsorbing CO_2 on coal surfaces, but the injected CO_2 can displace adsorbed methane, thus producing a valuable by-product and decreasing the overall cost of CO_2 sequestration. Because it has a large internal surface area, coal can store several times more CO_2 than the equivalent volume of a conventional gas reservoir.

To date, only a few experimental enhanced coal bed methane (ECBM) tests involving CO_2 injection have been conducted throughout the world. The sites for these tests show great potential for both CO_2 sequestration and ECBM production. Coal bed thickness is of great importance for ECBM production, both because thicker coal beds have greater volumes and, thus, yield more gas and because advanced production techniques are more applicable in thick coal beds. However, knowledge of this critical parameter is not available for the majority of deep unmineable coal seams.

CONSOL Energy Inc. has initiated a project on CO_2 ECBM production from unmineable coal seams. The world's CBM reserves are estimated at over 30,000 trillion ft^3, but much of this reserve is in coal seams deeper than 1000 m [6]. Efforts to produce CBM from these reservoirs have had only limited success because of very low reservoir permeability. A new approach, combining slant

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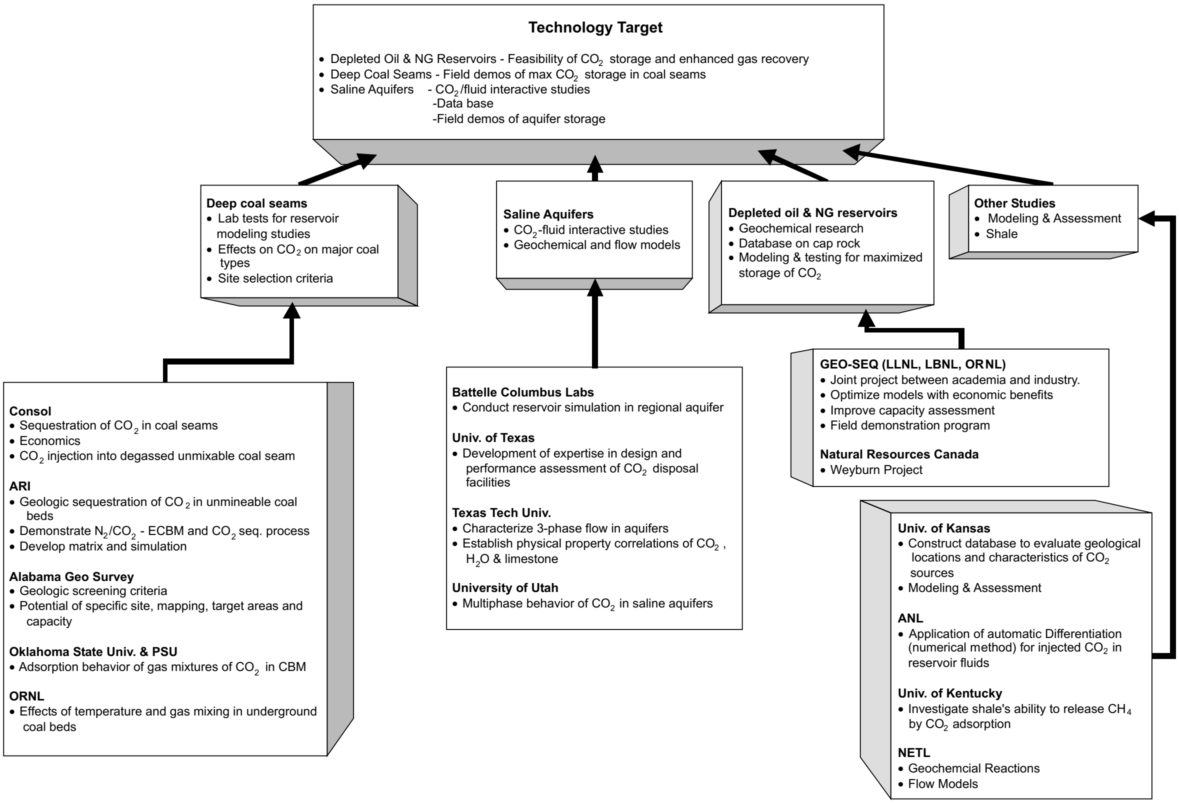

Fig. 4. Knowledge base and technology for CO_2 storage reservoirs.

(horizontal) holes, hydrofracing with coiled tubing and carbon dioxide flooding is proposed to produce gas from deep, low permeability reservoirs. The project's objectives are to demonstrate the applicability of CBM production using this novel approach and to demonstrate that the injected CO_2 remains sequestered at the intended location.

Advanced Resources International (ARI) is conducting an important project related to storing CO_2 in coal beds. The ARI project involves field testing of injection of CO_2, N_2 and CO_2/N_2 blends into coal seams. The reason for considering N_2 in addition to CO_2 is that N_2 is also an effective methane displacer, and N_2 makes up 80–90% of most flue gas. If flue gas could be sequestered without the need for CO_2 separation and capture, costs could be reduced. The work plan involves analyzing data from field tests at three locations to understand reservoir mechanisms. Technical issues that need to be addressed in this study are flue gas conditioning, compression, delivery and N_2/CH_4 separation. Flue gas injection appears to enhance methane production to a greater degree than is possible with CO_2 alone, while still sequestering CO_2. The information obtained will be used to develop a universal screening model to assess the potential for coal bed CO_2 sequestration in the US. Once developed, the model will be disseminated for use by others.

The Geological Survey of Alabama is conducting a project whose primary goals are to develop a screening model that is widely applicable, to quantify the CO_2 sequestration potential of the Black Warrior CBM region and to use the screening model to identify favorable CO_2 sequestration demonstration sites. The CBM region of the Black Warrior basin is a logical location to develop screening criteria and procedures. According to the US Environmental Protection Agency, Alabama ranks ninth nationally in CO_2 emissions from power plants, and two coal fired power plants are within the CBM region. Production from the Black Warrior basin is now leveling off, and CO_2 injection has the potential to offset the impending decline and extend the life and geographic extent of the region far beyond current projections.

Oklahoma State University is leading an effort to investigate and test the ability of injected CO_2 to enhance CBM production. The specific focus of this project is to investigate the competitive adsorption behavior of methane, CO_2 and nitrogen on a variety of coals. Measurements are focused on adsorption of the pure gases and various mixtures. Data will be taken on coals of varying physical properties at appropriate temperatures, pressures and gas compositions to identify the coals and conditions for which CO_2 sequestration applications are the most attractive.

Mathematical models are being developed to accurately describe the observed adsorption behavior. The combined experimental and modeling results will be generalized to provide a sound basis for performing reservoir simulation studies. These studies will evaluate the potential for injecting CO_2 or flue gas into coal beds to simultaneously sequester CO_2 and enhance CBM production. Future computer simulations will assess the technical and economic feasibility of coal bed CO_2 sequestration at specific candidate injection sites.

Oak Ridge National Laboratory (ORNL) is conducting a program aimed at acquiring critically important technical information for assessing the feasibility of sequestering CO_2 in deep unmineable coal beds. Since this carbon management technology is still in the development phase, fundamental and applied research programs are needed to fill major knowledge gaps. To enable reliable numerical modeling of CO_2 enhanced natural gas production, the effect of CO_2/methane mixing on gas pressure and sorption reactions in deep coal beds must be known quantitatively. Existing computer models are not adequate for this purpose, and experiments must be performed to obtain the data needed to upgrade these models. A significant part of this project involves autoclave measurement of the behavior of CO_2/methane mixtures. The data will be used to predict the behavior of CO_2 when injected into coal beds containing methane.

7. Sequestration in saline aquifers

Another option for geologic sequestration of CO_2 is in saline aquifers. The idea that large aquifers with good top seals can provide effective sequestration sites is a relatively new concept. About two thirds of the US is underlain by deep saline aquifers that have an estimated CO_2 sequestration potential of 5–500 billion tons [7]. Since the water from such aquifers is typically not suitable for irrigation and other uses, injection of CO_2 does not present a problem for potential future use. Because of the potential for CO_2 to dissolve in the aqueous phase, the storage capacity of saline aquifers is enhanced. However, there are a large number of uncertainties associated with the heterogeneous reactions that may occur between CO_2, brine and minerals in the surrounding strata, especially with respect to reaction kinetics.

There is a growing base of experience with CO_2 disposal in aquifers. One large project being carried out by Statoil involves recovering the CO_2 in natural gas from the Sleipner Vest offshore gas field in Norway at a rate of one million tonnes per year and reinjecting it into a nearby aquifer under the North Sea [8]. CO_2 migration is currently being monitored. Data from this project is contributing to the growing scientific confidence in the reliability of storing CO_2 in saline aquifers. However, more research, field testing, modeling and monitoring are needed to reduce the uncertainties relating to CO_2 storage in these formations.

Battelle Memorial Institute is managing an important project, the objective of which is to design an experimental CO_2 injection well and get it ready for permitting. Tasks involved include subsurface geologic assessment in the vicinity of the experimental site, seismic characterization of the site, borehole drilling to characterize the reservoir and cap rock formations, injection and monitoring system design and risk assessment. The proposed well site is to be located in the panhandle of West Virginia. This site has the advantage of providing access to both saline formations and deep coal beds. It is also in close proximity to a number of power plants that could serve as potential CO_2 sources. Another geologic factor in the vicinity of the site is the formation depth, at about 9000 ft, which provides significant cap rock containment potential and separation from freshwater. To obtain a more realistic assessment of CO_2 breakthrough, a 2-D seismic survey will be performed; a 3-D or 4-D survey will also be performed in preparation for future injection.

The Bureau of Economic Geology at the University of Texas is leading a research team to conduct a CO_2 sequestration field demonstration in a brine bearing formation near Houston, Texas. Two experiments will be conducted, the first involving a small volume of CO_2 using a single well for both injection and monitoring and the second using one well for injection and a second up-structure well for monitoring CO_2 migration. Response will be monitored both within the injection sandstone bed and in an overlying thin sandstone bed.

The study site provides for a rapid startup by using existing idle wells and has a low risk of adverse impacts because injection will take place in a hydrologically isolated reservoir compartment of a well known geologic structure. This project will extend the demonstration of modeling and monitoring capabilities for sequestration into a geologic formation for which very large scale sequestration is feasible in an area where significant CO_2 is produced. Texas is the state with the largest volume of CO_2 emissions [9].

Texas Technical University is conducting a project to develop a well logging technique using nuclear magnetic resonance (NMR) to characterize geologic formations, including the integrity and quality of the cap rock. Since well logging using NMR does not require coring, it can be performed more quickly and efficiently. Prior studies have identified several issues as impediments to the economic viability of sequestering CO_2 in deep saline aquifers and other geologic formations. These issues include the injection rate, the pressure required to achieve an economic throughput and how to assure the long term containment of CO_2. This research is aimed at determining suitable sites for injection of CO_2, sites at which artificial zones of high permeability can be created by controlled hydraulic fracturing. Hydraulic fracturing could reduce the number of injection wells required by an order of magnitude.

The University of Utah is heading a project that is studying naturally occurring CO_2 saline aquifers in the Colorado Plateau and Southern Rocky Mountains. These formations serve as natural analogs for CO_2 sequestration in saline aquifers. Studying them can provide much useful data to verify computer models. Also, natural leakage from these reservoirs is occurring, and studying these leaks can provide insight into the environmental problems caused by leaks and under what circumstances leaks can occur. The project also includes numerical simulation of CO_2 sequestration in these formations, including reactive modeling, that is modeling that accounts for chemical reactions between the formation rocks and CO_2.

8. Sequestration in depleted oil and gas reservoirs

Yet another option for geologic sequestration of CO_2 is in depleted oil and gas reservoirs. Since such formations are generally gas tight, the risk of leakage is expected to be minimal. Furthermore, there is the potential for enhanced oil and gas production, the sale of which can help mitigate sequestration costs. Most EOR projects in the US are in the Permian Basin of Texas. Most of the CO_2 for these projects is being transported by pipeline from natural CO_2 reservoirs in Colorado, New Mexico and Wyoming. It is anticipated that with high oil prices, recovery of CO_2 from the flue gas of coal burning power plants could be profitable for EOR use in the region.

The GEO-SEQ Project is being conducted by a consortium of national laboratories, educational institutions, and private industry firms. The project's goal is to reduce the cost of sequestration, develop a broad suite of sequestration options and ensure that long term sequestration practices are effective and do not introduce any new environmental problems. This objective is being approached by dividing the effort into four targeted interrelated tasks: cost optimization, monitoring technology, performance assessment models and capacity assessment. One important task is to develop methods for simultaneously optimizing sequestration of CO_2 in depleted oil and gas fields and increased oil and gas production. Such methods would have obvious multiple benefits. Results will lay the groundwork for rapidly evaluating performance at candidate sequestration sites, as well as monitoring the performance of CO_2 enhanced oil and gas recovery.

Natural Resources Canada is conducting a study of the injection of CO_2 into the Weyburn Unit. Understanding the mechanism, reservoir storage capability and the economics of CO_2 sequestration requires mapping the migration and distribution of the existing formation fluids, as well as the injected fluids. The project is focused on the acquisition of information from the enhanced oil recovery operation, on conducting geological, geophysical and geochemical assessments and on reservoir model simulations.

9. Other studies

DOE is also supporting other related studies. These mainly involve computer model development and project assessment.

The Midcontinent Interactive Digital Carbon Atlas and Relational Data Base (MIDCARB) is a joint project among the Geological Surveys of Illinois, Indiana, Kansas, Kentucky and Ohio being coordinated by the University of Kansas. The purpose of MIDCARB is to enable the evaluation of the potential for carbon sequestration in the participating states. When completed, the digital spatial data base will allow users to estimate the amount of CO_2 emitted by major sources in relation to geologic reservoirs that can provide safe and secure sequestration over geologic time periods. MIDCARB is organizing and enhancing critical information about CO_2

sources and developing the technology needed to access, query, model, analyze, display and distribute natural resource data related to carbon management.

Argonne National Laboratory is working on the development of improved computer models of the sequestration process. There is growing interest in linking reservoir flow models to geochemical models. If the formation has an aqueous phase, the injected CO_2 will dissolve in the reservoir liquid. In this case, the reactions of the CO_2-rich fluid with the host rock to form minerals should also be considered. More importantly, a geological CO_2 storage reservoir simulation must be effective in developing a design for optimal injection. The key element in finding the optimal CO_2 injection scheme is to work with an inverse modeling and sensitivity analysis tool for forward mode reservoir simulations.

Argonne National Laboratory is applying automatic differentiation (AD) as an alternative to the usual finite difference method of calculating derivatives. This technique will interface with existing geological CO_2 sequestration models to improve both the accuracy and speed of derivative computations. By using the new models generated by the AD method, it is possible to automatically determine the sensitivities of reservoir simulation output variables to any given independent input parameter, thus making the computer design of an optimal CO_2 storage scheme feasible.

The University of Kentucky Research Foundation is conducting an analysis of Devonian black shale in Kentucky for its potential for CO_2 sequestration and methane production. In testing the hypothesis that organic rich shales can adsorb significant amounts of CO_2 while releasing methane, the objective will be to characterize the shale, determine its CO_2 adsorption isotherm, the relationship of shale properties to CO_2 adsorption capacity, the effect of CO_2 adsorption on methane release and whether there are zones in the shale that have higher CO_2 adsorption capability and the extent of such zones.

The National Energy Technology Center (NETL) is pursuing a number of projects aimed at increasing the knowledge base relative to geologic sequestration of CO_2. One project, being conducted jointly with the US Geological Survey, has the objective of conducting an experimental study to assess the role of the chemistry of formation water on CO_2 solubility and the role of rock mineralogy in determining the potential for CO_2 sequestration through geochemical reactions. Another project being pursued in conjunction with a number of other organizations is aimed at providing guidelines for drilling new CBM production wells and determining what factors contribute to poor methane production/CO_2 sequestration performance. A third project, being conducted with West Virginia and Clarkson Universities, is aimed at building a system of flow equations relevant for core and field studies that incorporates unstable pore level flow patterns and to compare results with those of experiments and existing flow theory. A fourth project, involving Clarkson and Pennsylvania State Universities and CONSOL Energy Inc., has the objective to optimize the quantity of CO_2 that can be sequestered, the economic viability of coal bed sequestration, and the environmental acceptability of the technology.

10. BP carbon capture project, an example of integrated collaboration

An important cross-cutting driver for CO_2 sequestration R&D is integrated collaboration. An excellent example of this is the BP Carbon Capture Project (CCP). DOE is a partner in the CCP, an international technology development effort, involving the US, Norway and the European Union and directed toward the development of CO_2 capture and sequestration technology [10]. The objective is to share in program development in order to leverage funding, results and reduce duplication. BP, Chevron-Texaco, ENI (Italy), Shell, Norsk Hydro (Norway), Pan Canadian (Canada), Statoil (Norway) and Suncor (Canada) have formed the CCP, recognizing the advantages in pooling resources, experience and innovation to make the delivery of the needed technology more efficient and to provide the best opportunity for success.

The approach of the CCP is to define relevant scenarios and technology targets, solicit proposals and make awards. Technology teams, using various economic models, provide continuous project evaluation so that resources can be concentrated on the most promising technologies. Fig. 5 presents an overview of projects being conducted by the CCP. This figure shows that the CCP incorporates a wide spectrum of activities, involving all the areas already discussed. In general, these projects have smaller budgets and a shorter time frame than the projects discussed previously. The idea is to generate information that can feed into other development work as rapidly as possible.

Some projects are examining problems associated with long term monitoring and verification of formation integrity. A project is underway to develop a new method of monitoring gas injection

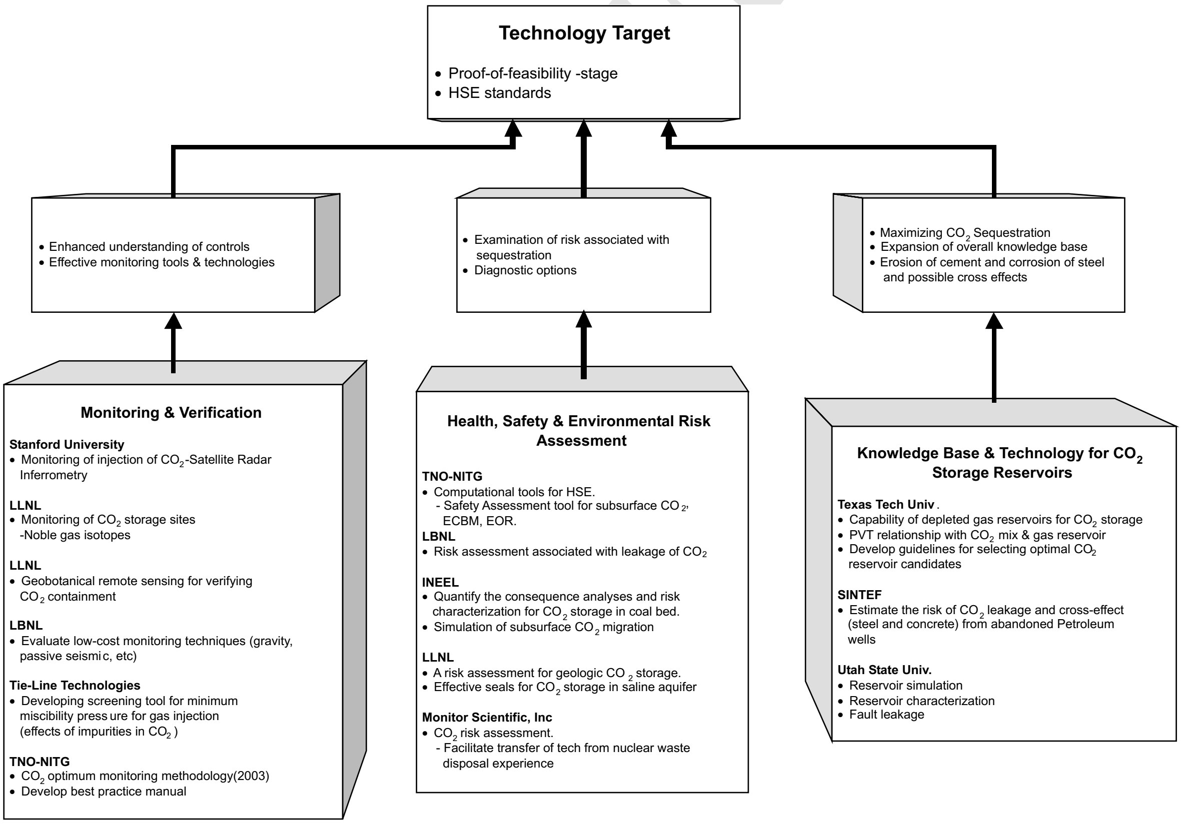

Fig. 5. BP carbon capture project (CCP).

using space borne satellite radar technology. This approach will permit observation of changes in surface elevation as small as 1 cm at 20 m spacing over an area 100 km square, so that the spatial distribution of elevation changes may be mapped in detail.

Another project is developing methodology and computational tools for health, safety and environmental risk assessment of geological CO_2 sequestration in various geologic strata of the North Sea region. This work will be integrated with the parallel system analysis activities of the Weyburn project.

11. Conclusions

The DOE Carbon Sequestration Program is developing a portfolio of technologies that hold great potential for the permanent sequestration of CO_2 in geologic formations. The programmatic timeline is to demonstrate a series of safe and cost effective greenhouse gas mitigation technologies at the commercial scale by 2012, with deployment leading to substantial market penetration beyond 2012. Developments are directed toward substantial improvement in performance and costs compared to the current state-of-the-art. Wide deployment of these technologies holds great promise to slow the growth of GHG emissions to the atmosphere in the near term while ultimately leading to stabilized emissions towards the middle of the 21st century. This paper has presented a brief overview of the portion of the DOE Carbon Sequestration Program dedicated to geologic storage of CO_2. More details on these and other R&D projects in the portfolio can be found at the referenced web site [2].

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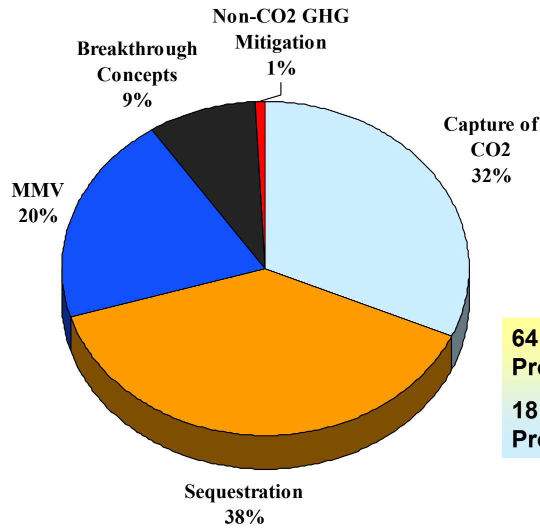
Carbon Sequestration
FY 02 Budget Total = $32.3 Million

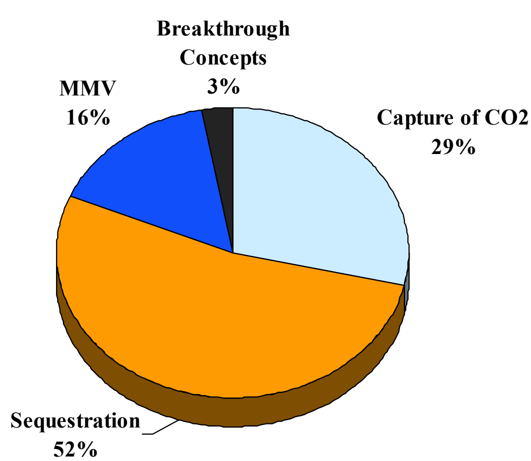


64 Contracted Projects

18 In-house Projects

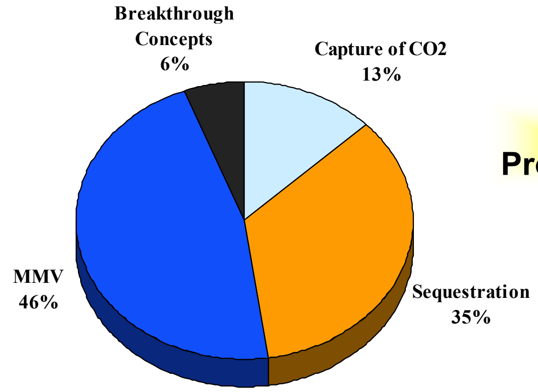
NETL 12/4/02

Carbon Sequestration
Focus Area
FY 02 Budget Total = $5.5 Million



NETL 12/4/02

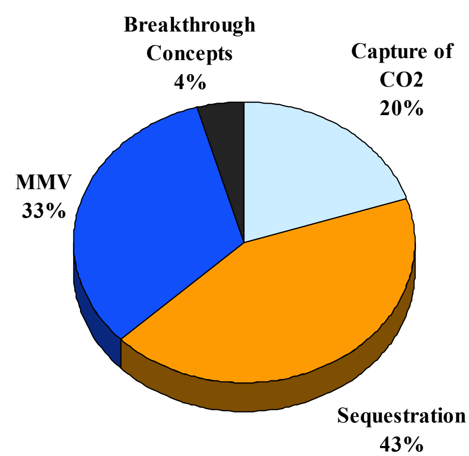
Carbon Sequestration National Laboratories FY 02 Budget Total = $6.9 Million



22 Projects

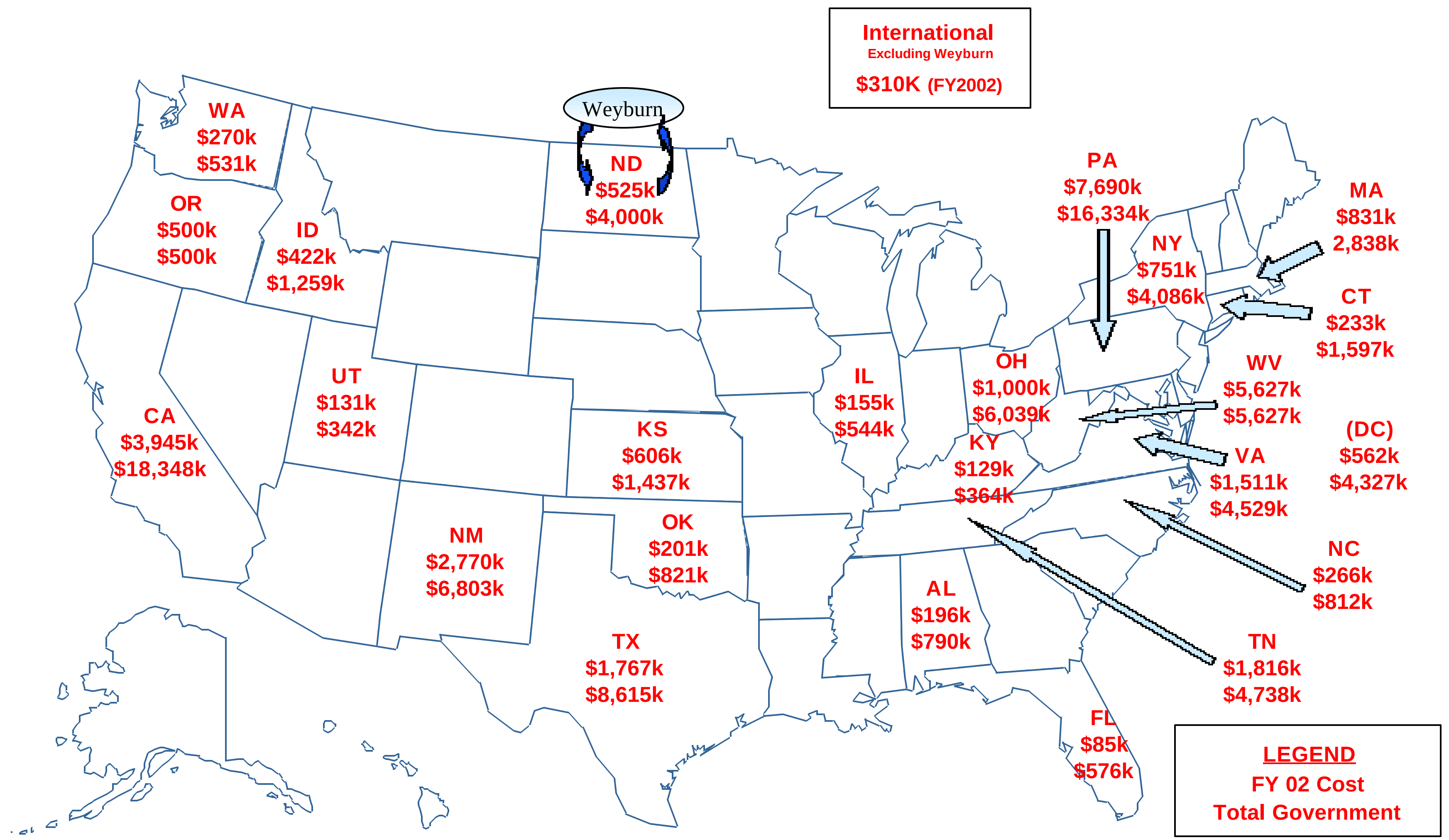
12/4/02

Carbon Sequestration Focus Area & National Laboratories FY 02 Budget Total = $12.3 Million



12/4/02

Carbon Sequestration State Budget Analysis



General/Mixed Fact Sheets

Technology Fact Sheets

- Coal Technologies Offer CO_2 Capture Benefits
- Coal-Based IGCC Offers CO_2 Capture Benefits for Oil Recovery

Program Fact Sheets

- Sequestration of Carbon Dioxide Emissions in Geologic Formations
- Terrestrial Sequestration Program
- Sequestration of Carbon Dioxide Emissions in the Ocean

R&D Fact Sheets

- Carbon Sequestration Science
- Sorbent and Catalyst Preparation Facilities
- Advanced Analytical Instrumentation and Facilities for In Situ Reaction Studies
- Small-Scale Facilities for Air Pollution Research
- Modular Carbon Dioxide Capture Facility

TECHNICAL
facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

10/2002

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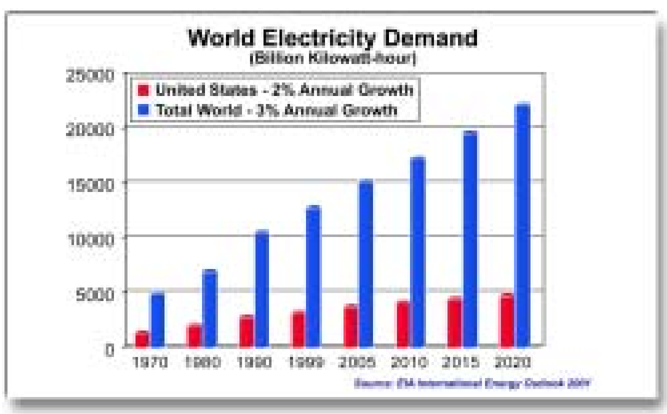
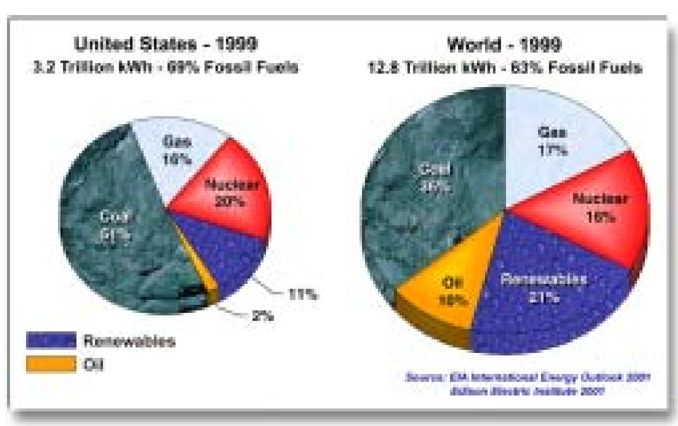
COAL TECHNOLOGIES OFFER CO_2 CAPTURE BENEFITS

With potential implications surrounding global climate change and carbon dioxide (CO_2), technology and policy options are being investigated for mitigating carbon dioxide emissions. Electric power generation represents one of the largest CO_2 contributors in the United States. Electricity consumption is expected to grow and fossil fuels will continue to be the dominant fuel source. Therefore, fossil fuel based power generation can be expected to provide an even greater CO_2 contribution into the future. Coal fuels more than half of this electric power generation capacity and typically produces the cheapest electricity among all fuel sources. Compared to other fossil fuels, coal suffers inherent CO_2 disadvantages relative to its combustion characteristics and the fact that most coal power plants are old and inefficient. These CO_2 disadvantages present a major challenge to coal-based power generation. Fortunately for coal, off-the-shelf CO_2 capture technologies provide performance and cost benefits for minimizing carbon dioxide emissions relative to other fossil fuel sources.



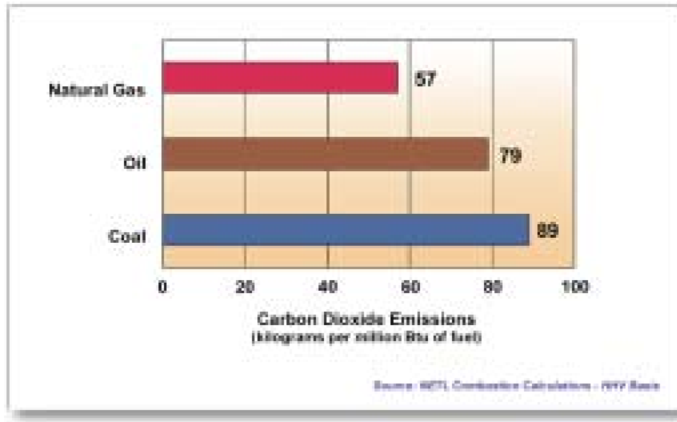
Electricity Use is Growing

Fossil Fuels: Dominant Energy Source for Electricity

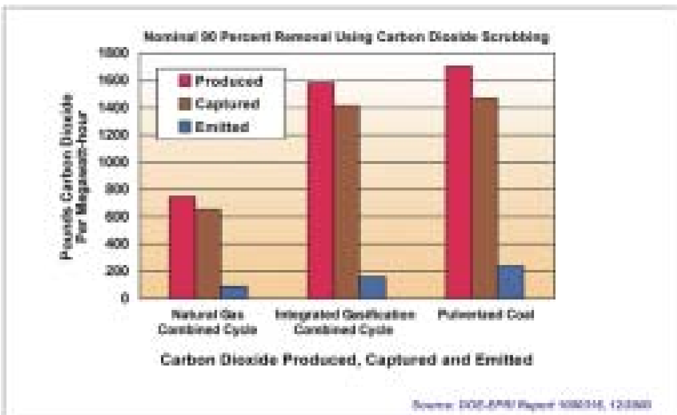


Coal Technologies Offer CO_2 Capture Benefits

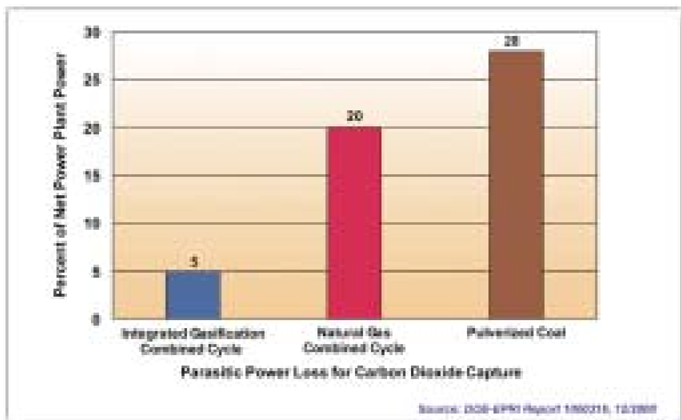
Coal & Electricity Are Major CO_2 Contributors



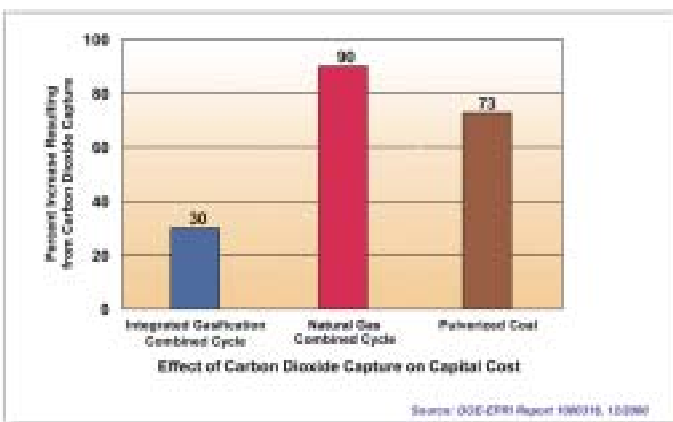
Fossil Fuel CO_2 Emissions



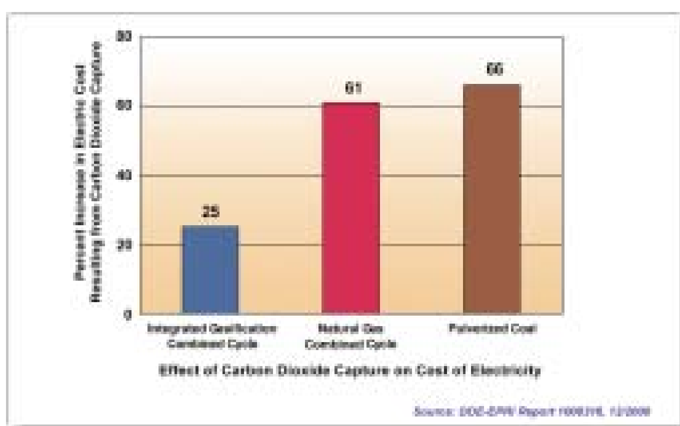
Substantial CO_2 Capture From Coal Power Plants



IGCC Minimizes Energy Penalty of CO_2 Capture



Coal Technologies Minimize Impact on Capital Cost



IGCC Minimizes Impact on Cost of Electricity

TECHNICAL
facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

10/2002

COAL-BASED IGCC OFFERS CO_2 CAPTURE BENEFITS FOR OIL RECOVERY

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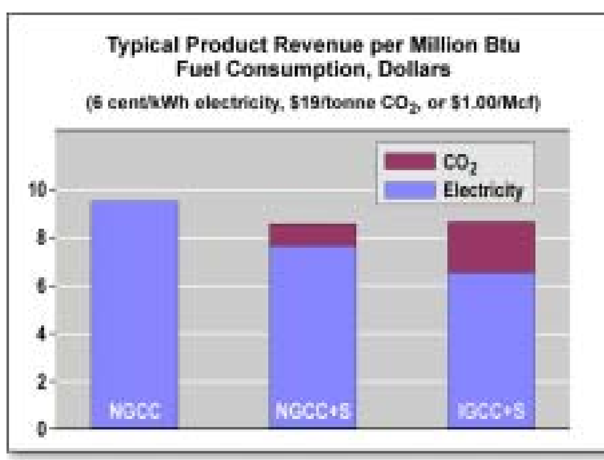
Background

As the demand for electricity steadily increases and concerns grow about greenhouse gas emissions, scientists are focusing on a coal-based technology that holds promise for addressing these issues. The technology, Integrated Gasification Combined Cycle equipped with a carbon capture and sequestration system (IGCC+S), can produce electricity at a competitive price, clean the environment of the most important greenhouse gas — carbon dioxide (CO_2) — and use the CO_2 as a valuable by-product to recover additional oil from mature reservoirs.

Scientists compared IGCC+S with two other approaches to determine how each would fare in a U.S. market that assumes an increased use of CO_2 to squeeze more oil out of mature reservoirs in a process called Enhanced Oil Recovery (EOR). The two other approaches were Natural Gas Combined Cycle (NGCC) and NGCC equipped with CO_2-capture technologies (NGCC+S). IGCC+S and NGCC+S, now in various phases of research and development, should be ready for commercialization within the decade. Selling the captured CO_2 for use in EOR projects could help offset the costs of these technologies while producing afford-able electricity and cleaning the environment.

At current and expected prices for natural gas, NGCC is the least expensive generating technology available. Economic projections show that it will provide the majority of additional generating capacity required by the United States over the next several decades. The present study was undertaken to determine if IGCC+S could be cost-competitive with NGCC if the captured CO_2 were marketable for use in EOR. This IGCC+S technology captures 90 percent of generated CO_2, which means that the net emission of CO_2 would only be about one-fifth as large per kilowatt-hour as emissions from NGCC.



Coal-Based IGCC Offers CO_2 Capture Benefits for Oil Recovery

Description

Scientists from the U.S. Department of Energy's (DOE) National Energy Technology Laboratory and the Pacific Northwest National Laboratory compared the economics of the three fossil-fuel technologies. They conducted the study to determine the price of electricity and the rate of return on invested capital expected for each of the three fossil-fuel systems. They further assumed that the systems would be built by 2010 and would operate for 20 years. Assumptions on fuel price, thermal efficiency, costs of coal and natural gas, and selling price of electricity and CO_2 were taken into account. The comparison resulted in the following conclusions.

NGCC's CO_2 emissions are less than half of those produced by an IGCC without carbon capture. But, an IGCC+S produces only one-fifth the carbon emissions of the most efficient NGCC. If reducing CO_2 emissions becomes important, an IGCC+S represents a significant improvement over NGCC.

NGCCs equipped to achieve 90 percent carbon capture are not as efficient as an IGCC+S, and the capital cost for providing capture is greater for NGCC than for IGCC. The cost difference is attributed to differences in the capture methods employed in the two generation approaches: from the flue gas in a NGCC and from a synthesis gas in an IGCC. The study indicates that the price of electricity generated by NGCC+S would be higher than that generated by either NGCC (without capture) or IGCC+S.

A large factor in the comparative costs of coal- and gas-based generation systems is fuel price. Compared with the price of oil and natural gas, the price of coal is expected to be stable. In fact, coal prices are expected to decline in the next two decades while the price of natural gas is projected to more than double for the same period. Price projections prepared by DOE's Energy Information Administration were used in the study. A large variability in the price of oil is also projected. In the study, the value of CO_2 for practice of EOR was estimated from published predictions of oil prices by using an historic linkage of prices for the two commodities.

Benefits

When they completed their study, the scientists concluded that IGCC+S could produce electricity profitably in a competitive market with no government subsidy for avoided carbon emissions, as is sometimes invoked as a means of bringing low carbon-emitting technology into the market. The profitability of NGCC is expected to be greater than that of IGCC+S, but uncertainty associated with the return on investment is greater for NGCC than for IGCC+S because of uncertainty of natural gas prices in the future. And finally, the potential for oil recovery is significant. When CO_2 is used for EOR, it can yield an additional 7 to 15 percent of the original oil in a reservoir and extend the life of the field by 15 to 30 years.

CO_2-EOR: The U.S. Landscape

- 66 Projects: > 190,000 bbl/day enhanced production
- 5 CO_2 Domes: > 1300 MMcfd, 30 TCF recoverable reserves (50+ years worth)
- Other CO_2 Sources
- CO_2 Pipeline Infrastructure

PROGRAM **facts**

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

10/2002

SEQUESTRATION OF CARBON DIOXIDE EMISSIONS IN GEOLOGIC FORMATIONS

Sequestration of Carbon Dioxide Emissions in Geologic Formations

This project is based on the fact that geologic formations, such as oil fields, coalbeds, and saline aquifers, are likely to provide the first large-scale opportunity to sequester concentrated CO_2 emissions. Researchers are trying to determine what effective, safe, and cost-competitive options are available for geologic storage of CO_2 emissions generated from coal, oil, and gas power plants. The research targets formations within 500 km of each power plant in the U.S. The U.S. goal is to reduce the cost of carbon sequestration to $10 or less per net ton of carbon by 2015.

Geologic Sequestration of CO_2 in Deep, Unminable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

Advanced Resources International, B-P Amoco and Shell Oil are using existing recovery technology to evaluate the viability of storing CO_2 in deep unminable coal seams in the San Juan Basin in northwest New Mexico and southwestern Colorado. The knowledge gained will be used to verify and validate gas storage mechanisms in coal reservoirs, and to develop a screening model to assess CO_2 sequestration potential.

Maximizing Storage Rate and Capacity, and Insuring the Environmental Integrity of Carbon Dioxide Sequestration in Geological Formations

Texas Tech University and its research partners are using nuclear-magnetic resonance well-logging techniques to identify suitable geologic formations for CO_2 storage. Understanding hydraulic fracturing will enable researchers to predict of the behavior of gas in targeted formations to minimize the number of injection wells, while increasing the injected gas volume.

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NETL

PROJECTS

Geologic Sequestration of CO_2 in Deep, Unminable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

Principal Investigator:
Scott Reeves, 713-780-0815

Partners: Advanced Resources International, Houston, Texas; B-P Amoco, Houston, Texas; Shell-CO_2 , Houston, Texas

Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide Sequestration in Geological Formations

Principal Investigator:
Alan Graham, 806-742-3553

Partners: Texas Tech University, Lubbock, Texas; Terra Tek, Salt Lake City, Utah; Sandia National Laboratory, Albuquerque, New Mexico; University of New Mexico, Albuquerque, New Mexico

Reactive, Multiphase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau

Principal Investigator:
Richard Allis, 801-581-7849

Partners: University of Utah, Energy and Geoscience Institute, Salt Lake City, UT; Industrial Research Limited (IRL), New Zealand

Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying the Potential of the Black Warrior Coalbed Methane Fairway, Alabama

Principal Investigator:
Jack Pashin, 205-349-2892

Partners: Geological Survey of Alabama, Tuscaloosa, AL; Alabama Power Company, Birmingham, Alabama; Jim Walter Resources, Brookwood, Alabama; University of Alabama, Birmingham, Alabama

Reactive, Multiphase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau

The University of Utah is leading an effort to conduct an in-depth study of deep saline reservoirs in the Colorado Plateau and Rocky Mountain region. The study will enable researchers to determine how much CO_2 can be stored, what happens to the stored gas, and the long-term environmental risks associated with the storage.

Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying the Potential of the Black Warrior Coalbed Methane Fairway, Alabama

The Geological Survey of Alabama and its partners are conducting research to determine the amount of CO_2 that can be stored in the Black Warrior coalbed methane region of Alabama. The effort is focused on developing a broad-based geologic screening model, quantifying CO_2 storage potential of the Black Warrior coalbed methane region, and applying the model to identify additional sites.

Experimental Evaluation of Chemical Sequestration of Carbon Dioxide in Deep Aquifer Media

This project involves Battelle Laboratories evaluating and examining factors that affect the geological and geochemical storage of CO_2 in deep saline formations in the Midwestern U.S. Research presently indicates that the most promising long-term option for sequestration is to dispose of CO_2 in a dense, supercritical phase in deep saline sandstone formations.

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers in the United States

The University of Texas at Austin's Bureau of Economic Geology is developing criteria for characterizing optimal conditions and characteristics of saline aquifers that can be used for long-term storage of CO_2. A regional U.S. data inventory of saline water-bearing formations is also being developed.

Sequestering Carbon Dioxide in Coalbeds

Oklahoma State University is leading an effort to develop, test, and investigate the ability of injected carbon dioxide to enhance coalbed methane production. The research will investigate competitive adsorption behavior of methane, CO_2, and nitrogen on the surface of a variety of coals to determine how much CO_2 is needed to displace the methane.

The GEO-SEQ Project

Lawrence Berkeley, Lawrence Livermore, and Oak Ridge National Laboratories and their partners are investigating safe and cost-effective methods for geologic sequestration of CO_2. Targeted tasks address the following: (1) Siting, selection, and longevity of the optimal sequestration sites; (2) lowering the cost of geologic storage; and (3) Identification and demonstration of cost-effective and innovative monitoring technologies to track migration of CO_2.

Geologic Sequestration of CO_2

Sandia National Laboratory and Los Alamos National Laboratory have partnered with an independent producer, Strata Production Company, to investigate down-hole injection of CO_2 into a depleted oil reservoir. A comprehensive suite of computer simulations, laboratory tests, field measurements, and monitoring efforts will be used to understand, predict, and monitor the geomechanical, geochemical, and hydrogeologic processes involved. The observations will be used to calibrate, modify, and validate the modeling and simulation tools.

Experimental Evaluation of Chemical Sequestration of Carbon Dioxide in Deep Aquifer Media

Principal Investigator:
Neeraj Gupta, 614-424-3820

Participant: Battelle Columbus Laboratories, Columbus, Ohio

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers in the United States

Principal Investigator:
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Participant: University of Texas at Austin, Bureau of Economic Geology, Austin, TX

Sequestering Carbon Dioxide in Coalbeds

Principal Investigators:
K. Gasem and R. Robinson, 405-744-9498

Partners: Oklahoma State University, Stillwater, Oklahoma; Pennsylvania State University, Department of Energy and Geo-Environmental Engineering, State College, PA

The GEO-SEQ Project

Principal Investigator:
Sally Benson, 510-486-7071/7714

Partners: Lawrence Berkeley National Laboratory, Berkley, California; Lawrence Livermore National Laboratory, Livermore, California; Oak Ridge National Laboratory, Oak Ridge, Tennessee; Stanford University, USGS, Texas Bureau of Economic Geology, Alberta Research Council, Chevron, Texaco, Pan Canadian Resources, Shell CO_2, BP-Amoco, and Statoil, Norway

Geologic Sequestration of CO_2

Principal Investigator:
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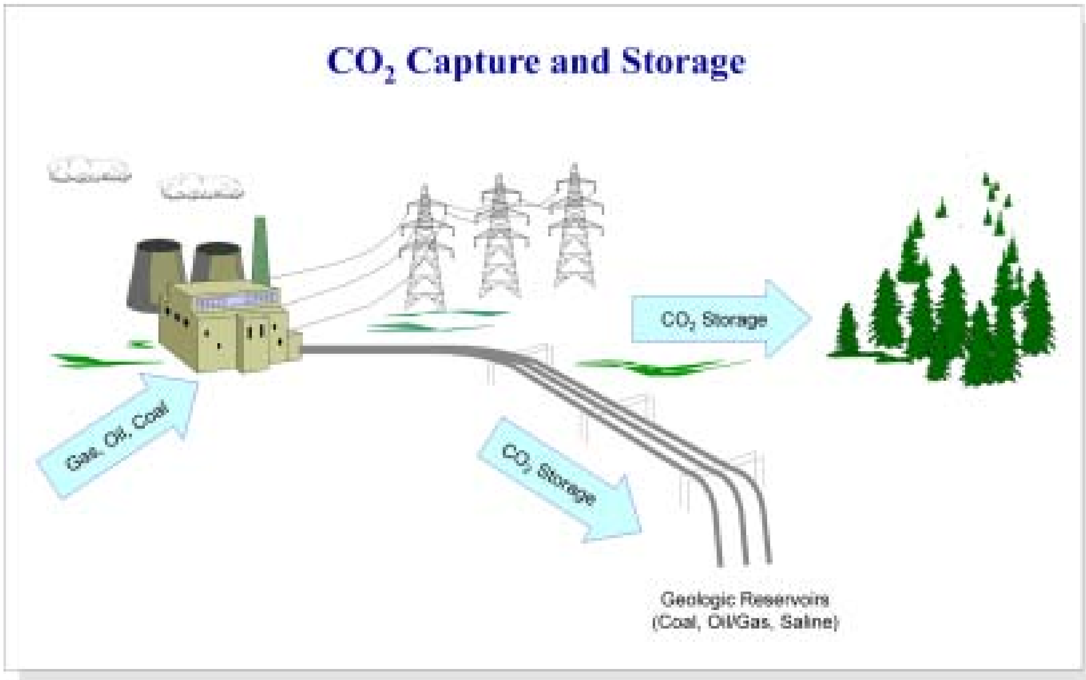
Partners: Sandia National Laboratory, Los Alamos National Laboratory, Strata Production Company

Sequestration of Carbon Dioxide Emissions in Geologic Formations



Range of Estimates for CO_2 Sequestration in U.S. Geologic Formations

Geologic Formation	Capacity Estimate (GtC)	Source
Deep saline reservoirs	1-130	Bergman and Winter 1995
Natural gas reservoirs in the United States	25 [a] 10 [b]	R.C. Burruss 1977
Active gas fields in the United States	0.3 / year [c]	Baes et al. 1980
Enhanced coal-bed methane production in the United States	10	Stevens, Kuuskraa, and Spector 1998

a. Assuming all gas capacity in the United States is used for sequestration
b. Assuming cumulative production of natural gas is replaced by CO_2
c. Assuming that produced natural gas is replaced by CO_2 at the original reservoir pressure

PROGRAM facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

10/2002

TERRESTRIAL SEQUESTRATION PROGRAM

Capture and Storage of Carbon in Terrestrial Ecosystems

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Background

Clean, affordable energy is essential for U.S. prosperity and security in the 21st century. Over half of the electricity in the U.S. currently comes from coal-fired boilers, with coal projected to account for over half of U.S. electricity generation through 2020 and beyond. From a global perspective, in developing nations coal use for electricity generation is projected to more than double by 2020. This continuing demand for fossil-fuel-based power and the associated rise in atmospheric carbon dioxide (CO_2) concentrations will require innovative ways to capture and store carbon.

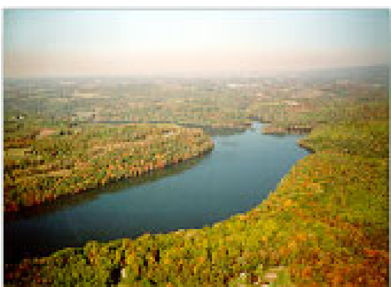
Terrestrial ecosystems, which include both soil and vegetation, are widely recognized as a major biological "scrubber" for CO_2. Terrestrial sequestration is defined as either the net removal of CO_2 from the atmosphere or the prevention of CO_2 emissions from leaving terrestrial ecosystems. Sequestration can be enhanced in four ways: reversing land use patterns; reducing the decomposition of organic matter; increasing the photosynthetic carbon fixation of trees and other vegetation; and creating energy offsets using biomass for fuels and other products. The terrestrial biosphere is estimated to sequester large amounts of carbon, about 2 billion tons (2 Gt) of carbon annually. The total amount of carbon stored in soils and vegetation throughout the world is estimated to be about 2,000 Gt +/- 500.

NETL

CONCURRENT BENEFITS

Terrestrial sequestration also offers significant additional benefits including:

- Creating wildlife habitat and green space
- Preventing soil erosion and stream sedimentation
- Boosting local and regional economies
- Reclaiming poorly managed lands
- Increasing recreational value of lands



Program Goal

"To provide economically competitive and environmentally safe options for offsetting the projected growth in CO_2 emissions."

Description

The U.S. Department of Energy's Office of Fossil Energy (FE) and Office of Science are jointly carrying out research on the capture and storage of carbon in terrestrial ecosystems. FE's current activities, which are managed by the National Energy Technology Laboratory (NETL), focus on enhancing the productivity of terrestrial ecosystems through the application of soil amendments, such as coal-combustion byproducts and biosolids produced at wastewater treatment facilities. The goal of the program is to provide economically competitive and environmentally safe options for offsetting the projected growth in CO_2 emissions. The cost of the options is in the range of $10/ton of avoided net costs for sequestration. The efforts are based on fostering partnerships between landowners, biomass and biofuels industry representatives, government agencies, and energy producers, such as coal companies and utilities. This partnering will help to determine the best approaches for increasing the amount of carbon sequestered in soils and vegetation.

Project Summaries

Applied Terrestrial Sequestration Partnership

The Applied Terrestrial Sequestration Partnership, an integrated research program led by Los Alamos National Laboratory (LANL)and NETL, is taking a leading role in developing breakthrough technologies and applications for terrestrial carbon sequestration.

Ecosystem Dynamics Understanding both ecosystem dynamics and economic issues is critical to the success of terrestrial sequestration as a policy option. Marginal lands (forest, farm, range, or industrial) can serve as a barometer for climate change and are ideal field sites for investigating terrestrial sequestration. This study uses a multi-disciplinary approach, integrating lab and field studies with the CENTURY model. The result will be a fundamental understanding of how changes in the plant community are reflected in carbon inventories and a detailed economic analysis of carbon sequestration in reclamation sites.

Advanced Plant Growth The research team, including partners at the Ohio State University, the University of Southern Maine, the National Energy Technology Laboratory, and the University of California at San Louis Obispo uses plant metabolites to optimize terrestrial carbon sequestration at reclamation sites. Metabolites will increase plant growth rates, biomass volume, and carbon dioxide uptake–maximizing sequestration potential. DNA-based methods are being used to fingerprint soil bacterial and identify their role in nutrient recycling. Field studies assess microbial response to changing water and temperature conditions.

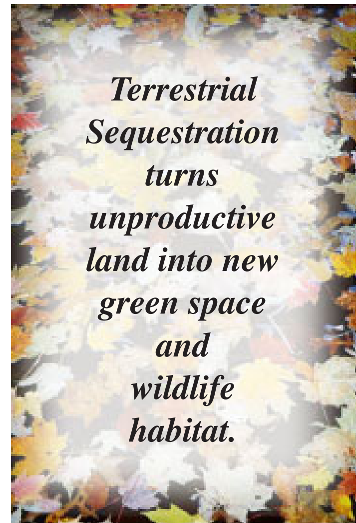
Soil Carbon Measurements An integrated research team is working to develop new field-deployable, laser-based instruments for measurement and characterization of soil carbon. These instruments will revolutionize the practice of soil carbon science and allow for a more accurate accounting for terrestrial carbon sequestration. Instruments will be calibrated to a wide variety of soils and tested in the field. Results will be compared with traditional carbon measurements with respect to accuracy, cost, and time.

Enhancing Carbon Sequestration and Reclamation of Degraded Lands with Fossil Fuel Combustion Systems

Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) are teaming with Ohio State University and Virginia Polytechnic Institute to determine the best way to increase the carbon sequestration potential of land previously disturbed by mining, highway construction, or poor land management practices. The team will focus on the use of amendments derived from paper production, biological waste treatment facilities, and solid byproducts from fossil-fuel combustion to identify and quantify the key factors necessary for the successful reclamation of degraded lands. The results will be summarized in a set of guidelines containing practical information about matching amendment combinations to land types and optimum site-management practices. Long-term field studies will be designed and site(s) recommended for the demonstration and further optimization. (ORNL and PNNL are part of DOE's Center for Enhancing Carbon Sequestration in Terrestrial Ecosystems [CSiTE] which is run by the DOE Office of Science.)

Carbon Capture and Water Emissions Treatment System at Fossil-Fueled Electric Generating Plants

The Tennessee Valley Authority and EPRI are partnering to demonstrate and assess the life-cycle costs of integrating electricity production with enhanced terrestrial carbon sequestration. The project is being conducted on coalmine spoil land at the 2,558 megawatt (MW) Paradise Station (Kentucky). This station, which burns bituminous coal and is currently equipped with flue gas desulfurization (FGD) for SO_2 control and is set to begin using selective catalytic reduction for NO_x control, will use the byproducts from these control systems to amend the mine soils. Treated water generated by the FGD system will be used to irrigate the soils. Benefits include: use CCBs to improve reclamation sites and carbon sequestration, development of a passive technology for criteria pollutant release reduction in water, development of a wildlife habitat and green space, generation of Total Maximum Daily Load (TMDL) credits for water and airborne nitrogen, and development of additional forest lands.



Enhancement of Terrestrial Carbon Sinks through Reclamation of Abandoned Mine Lands in the Appalachian Region

Stephen F. Austin State University, working with TXU (Texas Utilities) and Westvaco, is investigating storing carbon in trees on abandoned mine lands in the Appalachian region. Researchers are studying the potential for reclamation and reforestation and the development of a free-trade system for carbon credits. The focus is on developing an environmentally safe way to use mined lands and accomplish long-term carbon sequestration. Growth and yield models will be applied to commercial tree species in order to quantify the maximum amount of carbon that can be stored. Discounted cash-flow analyses will be conducted and the soil expectation value will be calculated to predict the per ton cost of carbon sequestration. A "carbon credit" market between landowners and utility and coal companies will be investigated, as well as analysis of the impact of sequestration on the local economy.

Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration

The Nature Conservancy will be working in close collaboration with U.S. based companies (including General Motors and American Electric Power) and NGO partners to study how carbon dioxide can be stored more effectively by changing land use practices and investing in forestry projects. The project will focus on gaining cost-effective, verified measurements of the long-term potential of various carbon sequestration and land use emissions avoidance strategies. The project will use newly developed aerial and satellite-based technology to study forestry projects in Brazil and Belize to determine their carbon sequestration potential, and will also test new software models to predict how soil and vegetation store carbon at sites in the United States and abroad.

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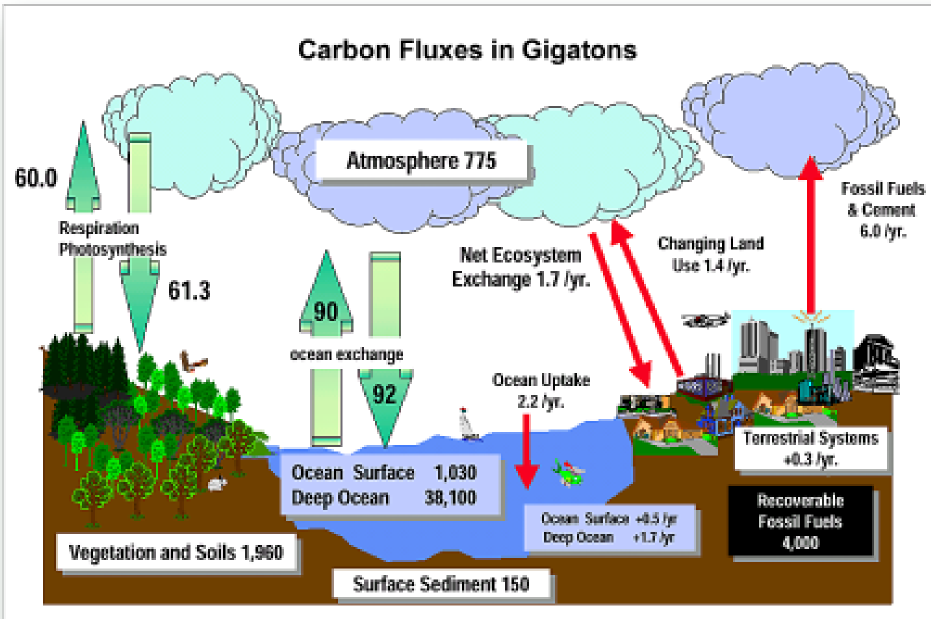
Terrestrial Sequestration Program

Capture and Storage of Carbon in Terrestrial Ecosystems



The Global Carbon Cycle

The figure above presents a simplified version of the global carbon cycle. The large arrows represent natural paths of carbon exchange and the small arrows represent the human or anthropogenic contributions to the carbon cycle. The flow of carbon is measured in billions of metric tons (gigatons).

The locations where carbon is stored are called "sinks."

These carbon "sinks" are immense. The atmosphere contains about 750 billion metric tons of carbon dioxide, the ground contains about 2,190 billion metric tons of carbon dioxide, and the oceans contain about 40,000 billion metric tons of carbon dioxide.

The arrows show the yearly exchange between these sinks. Plants and soils "give" about 60.0 billion metric tons of carbon dioxide to the atmosphere and "take" about 61.3 billion metric tons of carbon dioxide. The difference is the ability of green plants to "fix" carbon by photosynthesis.

The ocean absorbs 92 billion metric tons of carbon dioxide, which is slightly more than the 90 billion metric tons of carbon dioxide that is absorbed by the water. These are the main "fluxes" or flows of carbon that occur in nature.

The anthropogenic flux of carbon comes from two major sources. The larger of the two is from the burning of fossil fuels for electricity and cement production at 5.5 billion metric tons of carbon dioxide per year that is released to the atmosphere. The smaller of the two is the exchange of this carbon dioxide from land use changes that results in 1.4 billion metric tons of carbon dioxide being released to the atmosphere. 1.7 billion metric tons of carbon dioxide is absorbed by the land, resulting in a net exchange of +0.3 billion metric tons per year.

PROGRAM facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

10/2002

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SEQUESTRATION OF CARBON DIOXIDE EMISSIONS IN THE OCEAN

Description

The world's oceans represent the largest potential sink for the carbon dioxide (CO_2) produced by human activities. Already oceans contain the equivalent of an estimated 140,000 gigatons of CO_2. The ocean's natural carbon transfer processes have spans of thousands of years and will eventually transfer 80-90 percent of today's man-made (anthropogenic) CO_2 emissions to the deep ocean. This natural CO_2 transfer may already be adversely affecting marine life near the ocean and could also be altering deep ocean circulation patterns.

The effectiveness of ocean storage techniques depends largely on how long the CO_2 would remain in the ocean. Most studies indicate that if CO_2 can be injected into deep oceanic water circulation, it will remain there for approximately 1000 years.

Direct injection of CO_2 into the ocean would reduce both atmospheric CO_2 concentrations and their sharp rate of increase. The purpose of this program is to investigate the technical, economic and environmental feasibility of CO_2 sequestration in the deep ocean, primarily by deep injection.

Projects

Feasibility of Large Scale Ocean Sequestration: Experiments on the Ocean Disposal of Fossil Fuel CO_2

Monterey Bay Aquarium Research Institute will use the Remotely Operated Vehicle (ROV) to carry out pilot experiments involving the deployment of small quantities of liquid CO_2 in the deep ocean for the purposes of investigating the fundamental science underlying concepts of ocean CO_2 sequestration. Below a depth of about 3000m the density of liquid CO_2 exceeds that of seawater, and the liquid CO_2 is quickly converted into a solid hydrate by reacting with the surrounding water.

Feasibility of Large Scale Ocean Sequestration: Optimized In Site Raman Spectroscopy on the Sea Floor and Effects of Clathrate Hydrates on Sediment

The research group at Washington University in St. Louis will work with MBARI to carry out the first direct in situ analysis on the seafloor of CO_2 clathrate hydrates, their entrained and surrounding fluids, along with sediments adjacent to the clathrate hydrates, using a Raman spectrometer. This information on the physical chemical of clathrate hydrates and clathrate sediment interaction is essential for the evaluation of CO_2 ocean sequestration.

Sequestration of Carbon Dioxide Emissions in the Ocean

Accelerated Carbonated Dissolution as CO_2 Capture and Sequestration Strategy

Lawrence Livermore National Laboratory and the U.S. Geological Survey will conduct a laboratory program to synthesize and study the physical properties of CO_2 hydrates, and will contrast these properties of methane hydrates. Gas-solid exchange experiments will methane hydrates to determine whether methane extraction from natural gas and CO_2 sequestration can be accomplished in a single step.

Large Scale CO_2 Transportation and Deep Ocean Sequestration

The objective of the project is to investigate the techno-economic viability of large-scale carbon dioxide transportation and deep ocean sequestration. Two cases are being investigated; one involving ocean tanker transport of liquid CO_2 to an offshore floating platform on a barge with vertical injection to the ocean floor and the other involving transporting liquid CO_2 through undersea pipelines to the bottom of the ocean.

Ocean Carbon Sequestration

The objective of this project is to provide logistical and technical support for the International Collaboration Project on CO_2 Ocean Sequestration. Such support includes providing a surface vessel for the project, biological experiments and a survey of potential test sites.

International collaboration Project on CO_2 Ocean Sequestration

The objective of this project is to develop instrumentation and potential experiments for the International Project on CO_2 Ocean Sequestration. This international effort involves four nations (United States, Japan, Norway, and Canada) and one private corporation, CABB of Switzerland. The field experiment is scheduled to take place in the summer of the year 2001, at Keahole Point on the Kana Coast off the big island of Hawaii.

Public Outreach and Permitting

The objective of this project is to conduct the public outreach and permitting activities associated with the International Project on CO_2 Ocean Sequestration. This effort although primarily conducted on the large island of Hawaii, is also being carried out within the state of Hawaii and on the continental United States.

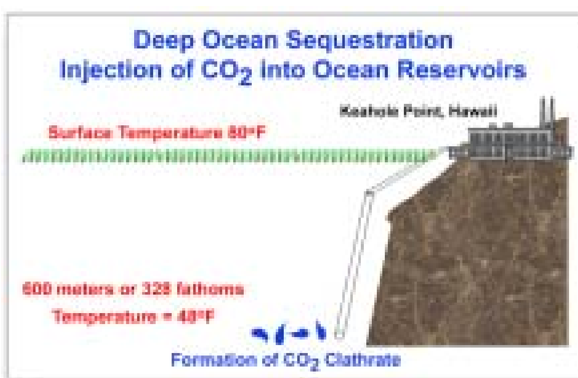

Figure 1 presents the basic idea of ocean based sequestration. While the surface of the ocean (near Hawaii) is at the perfect temperature of 80 degrees F for a vacation, the temperature at 600 meters is a cold 48 degrees Fahrenheit. Water pressure increases with depth and at 600 meter below the surface, the water pressure is sufficient to keep CO_2 in the liquid or solid state.

PROJECTS

Feasibility of Large-Scale Ocean CO_2 Sequestration: Experiments on the Ocean Disposal of Fossil Fuel CO_2
Principal Investigator:
Dr. Peter Brewer, 831-775-1706
Partner: Monterey Bay Aquarium Research Institute

Feasibility of Large-Scale Ocean CO_2 Sequestration: Optimized in Situ Raman Spectroscopy on the Seafloor and Effects of Clathrate Hydrate on Sediment
Principal Investigator:
Prof. Jill Pasteris, 316-935-5889
Partner: University of Washington at St. Louis

Accelerated Carbonate Dissolution as CO_2 Capture and Sequestration Strategies
Principal Investigator:
Terry Surles, 925-423-1615
Partners: Lawrence Livermore National Laboratory (LLNL), and U.S. Geological Survey (USGS)

Large Scale CO_2 Transportation and Deep Ocean Sequestration
Principal Investigator:
Hamid Sarv, 330-821-9110
Partners: McDermott Technology, Inc., and University of Hawaii

Ocean Carbon Sequestration
Principal Investigator:
Rick Coffin, 202-767-0065
Partner: Naval Research Laboratory

International Collaboration Project on CO_2 Sequestration
Principal Investigator:
Howard Herzog, 617-253-0688

Public Outreach and Permitting
Principal Investigator:
Gerard Nihous, 808-539-3874
Partner: Pacific International Center for High Technology Research (PICHTR)

PROGRAM **facts**

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Mineral Sequestration

07/2000

MINERAL CARBONATION STUDY PROGRAM

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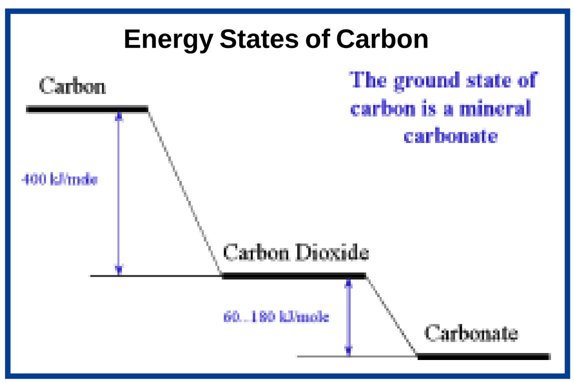
MINERAL SEQUESTRATION HOMEPAGE

http://www.fe.doe.gov/products/gcc/index.html

Description

The availability of clean, affordable energy is essential for the prosperity and security of the United States, as well as the rest of the world. About 85% of the energy used in the US is derived from fossil fuels, and continued dependence on these fuels is expected well into the 21st century. The continuing demand for energy and the associated rising CO_2 concentration in the atmosphere may have potentially large impacts on climate change. Comprehensive measures, including CO_2 sequestration, would be required to reduce CO_2 emissions while sustaining the demand for energy. Several methods have been suggested for sequestering CO_2, all of which have advantages and disadvantages. Among them, mineral carbonation is a relatively new and less-studied method with potential to sequester substantial amounts of CO_2.

Mineral carbonation, alternately referred to as Mineral Sequestration, is the reaction of CO_2 with non-carbonate minerals such as olivine and serpentine to form geologically stable mineral carbonates. Mineral carbonation could be realized in two ways. First, minerals could be mixed and reacted with CO_2 in a process plant. Second, CO_2 could be injected into selected underground mineral deposits for carbonation, similar to geological sequestration. Using mineral carbonation to reduce CO_2 emissions has many potential advantages such as:



Mineral Carbonization occurs naturally

Long Term Stability. Mineral carbonates, the product of this process, are known to be stable over geological time frames. This process ensures permanent fixation rather than temporary storage of CO_2, thereby guaranteeing no legacy issues for future generations. Mineral carbonation mimics the natural weathering of rock.

Vast Capacity. The raw materials for binding CO_2 exist in vast quantities across the globe. Readily accessible deposits exist in quantities that far exceed even the most optimistic estimates of coal reserves.

Potential to Become Economically Viable. The overall process is exothermic and, hence, has the potential to become economically viable. In addition, its potential to produce value-added by-products during the carbonation process, such as strategically important metals, may further reduce its costs.

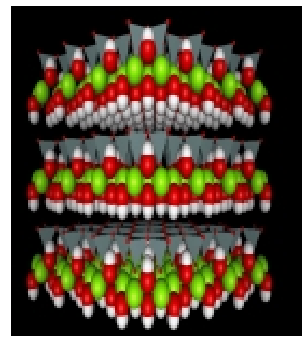
MINERAL CARBONATION STUDY PROGRAM

Despite these advantages, mineral carbonation processes will be practical only when two key issues are resolved. First, for sequestration purposes, a fast reaction route that optimizes energy management must be found. Second, issues with respect to the mining and processing activities required for mineral sequestration need to be quantified, especially concerns related to overall economics and environmental impact.

Goals

The primary goal of the mineral carbonation study is to generate a useful knowledge base that can lead to development of mineral CO_2 sequestration methods. To achieve this goal, the reaction mechanisms, heat requirements and environmental interactions must be understood well enough to permit engineering process development. A secondary goal is to acquire knowledge essential to understanding the reactions of CO_2 with underground minerals, in support of the U.S. Department of Energy's geological sequestration programs where CO_2 may be injected to deep saline aquifers or depleted oil or gas reservoirs. Knowledge of the reaction characteristics of CO_2 with various minerals at elevated pressures and temperatures such as those found deep underground will help scientists predict the long-term effects of such practices.

Elements



$Mg_3Si_2O_3(OH)$ - Atomic representation of serpentine structure (commonly called Lizardite)

The team of researchers comprising this working group are pooling their knowledge and experimental capabilities in order to effectively conduct the structured program outlined below.

Study of Carbonation Reactions**.** Progress to date has been extremely encouraging. It has been found that finely ground serpentine $Mg_3Si_2O_5(OH)_4$, or olivine Mg_2SiO_4, will react with CO_2 in solutions of supercritical CO_2 and water to form magnesium carbonate $MgCO_3$. The reaction can be summarized as

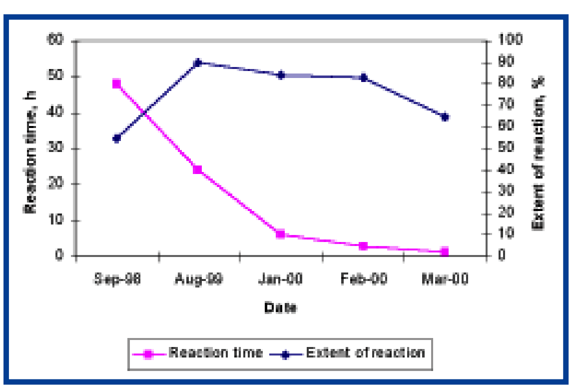
$$1/3\ Mg_3Si_2O_5(OH)_4 + CO_2 \text{ -----> } MgCO_3 + 2/3\ SiO_2 + 2/3\ H_2O$$

When the program first started, it required 24 hours to produce a 50% carbonation level using an olivine feedstock, reaction temperatures of 150-250°C and pressures of 85-100 bar. Through careful control of solution chemistry, the process has been accelerated so that 84% conversion of olivine can be achieved in just 6 hours. Furthermore, when heat pretreated serpentine is reacted using the same enhanced reaction process, approximately 80% conversion occurs in less than an hour. Carbonation studies are continuing utilizing highly instrumented reactors and atomic level simulations to optimize reaction conditions, and explore the use of catalysts and alternative feedstocks.

System Feasibility**.** A life cycle assessment is under way to establish the feasibility of the baseline mineral sequestration concept with respect to system costs, development requirements and environmental attributes.

Feedstock Characterization**.** Specific mineral deposits are being identified and characterized based upon potential co-location of mines and sequestration plants with fossil power plants. In addition, potential feedstock sources from industrial byproducts and waste streams are being examined.

These efforts are being conducted as part of Fossil Energy's Advanced Research and Technology Development efforts. The Mineral Carbonation Program is being managed through the National Energy Technology Laboratory's Environmental Product Division and is supported by the Coal Utilization Science, University Coal Research, and the Advanced Metallurgical Processes programs. The activities of the working group are being coordinated by the CUS program. Note that the group is seeking to interact with other interested researchers and industry stakeholders as a means to increase overall program scope and impact.



Mineral carbonation reaction time has been reduced from 48 hours to one hour over the period from Sept. 1998 to March 2000 at the Albany Research Center.

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National Energy Technology Laboratory

Sequestration

06/2002

Carbon Sequestration Science

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NETL

Description

The goal of the Carbon Sequestration Science focus area is to identify and remove technical barriers and reduce costs associated with sequestration of carbon from energy processes. Effective carbon sequestration technologies and methods will provide long-range options for reducing CO_2 emissions from large stationary sources of CO_2. These reductions will ensure the continued availability of low-cost energy from the plentiful fossil energy resources within the United States.

Research at the Carbon Sequestration Science Laboratory will emphasize CO_2 separation and capture technologies, geological storage science, development of direct ocean storage approaches, and integrated process modeling, simulation and economic assessment. This research will stimulate innovation and develop novel concepts for carbon sequestration by partnering with universities, Federal laboratories, and private industry. Activities will span the broad carbon sequestration interest area and will focus on improving scientific understanding of the separation and capture of CO_2, the disposal of CO_2 in the deep oceans, and geologic sequestration.

As a part of this national research activity, the focus area for Carbon Sequestration Science will conduct research ranging from fundamental studies to small-scale proof-of-concept research on selected processing options. Systems analysis via computer modeling and simulation of approaches to carbon sequestration will be developed in-house for use in evaluating the various approaches.

The purpose of the Carbon Sequestration focus area at the NETL is to serve as the focal point for all carbon sequestration R&D activities performed with in-house resources sponsored primarily by the Office of Fossil Energy. Its specific role is to:

- Identify research directions and construct a balanced portfolio of activities integrated with the national sequestration R&D program,
- Conduct portions of the R&D portfolio with in-house resources,
- Serve as a hub for the conduct of systems analysis on sequestration technology options.

Carbon Sequestration Science

Benefits

- Generate ideas and build expertise
- Refine program focus as promising approaches emerge
- Provide scientific basis to define and develop pilot-scale activities
- Strengthen existing partnerships
- Facilitate regional NETL/University/Industry partnerships
- Increase participation in key international activities

Goal

Our goal is to have the Carbon Sequestration Science focus area, including its partners, recognized as the premier research laboratory in the area of carbon sequestration. This will be accomplished by:

- Providing scientific insights that lead to technological options for long-term stabilization of CO_2 and other GHG's,
  - provide scientific basis for sequestration to allow continued use of fossil energy resources,
  - develop scientific understanding of processes for separation, capture, reuse, and storage of CO_2 and other GHG's, and,
  - address geological, chemical, and biological sequestration barrier issues.
- Ensuring full attention to potential consequences of sequestration options,
- Providing scientific information and systems analysis from a non-conflicted perspective.

A continuing investment in this focus area will result in the identification of CO_2 capture technologies and sequestration methods that are technically feasible, environmentally acceptable, and economically well defined. Should national decisions be made regarding the need to sequester CO_2, then the capture and sequestration techniques developed as a result of this R&D activity can be deployed commercially in the U.S. and abroad.

Milestones

- In FY2001, the low and high-pressure water tunnel laboratories will be completed. Determine the fate of CO_2 in the ocean water column; evaluate microbes in coal seams; develop simulation models of CO_2 displacement of coal-bed methane; evaluate the effect of ground water pH on coal seam sequestration capacity; and study formation of metal carbonates during reaction of CO_2 with minerals high Ca and Mg.
- In FY2002, the Capture and Geologic Storage laboratories will be completed. Determine the influence of minor flue gas constituents on hydrate formation; study the effects of coal variability (e.g., rank) on sequestration capacity; optimize parameters for CO_2 or multipollutant wet scrubbing; and evaluate the potential for using high volume waste materials (e.g., FGD sludge and fly ash) in sequestration.
- In FY2003, capture and storage research activities will be initiated and work to install the Integrated Carbon Sequestration Test Facility is initiated. Complete the coal seam simulation model (including trace gas components); investigate acid mine drainage (AMD) waters (high in metals content) as a sink for CO_2; evaluate the use of standard pipelines to transport flue gas to sequestration sites; evaluate the effect of trace amounts of SO_2 and NOx on corrosion of CO_2 pipelines and identification of initial capture technologies for joint scale-up Federal/ partnership evaluation.
- In FY2004, assembly of the Integrated Carbon Sequestration Test Facility continues. A novel dry-scrubbing process is investigated for CO_2 removal from simulated Vision 21 gas streams; verify simulation model with experimental results; and improve the kinetics of CO_2-mineral sequestration reactions.
- In FY2005, testing of promising process concepts will be initiated in the Integrated Carbon Sequestration Research Facility. Develop universal flow equations for injection of CO_2 into geologic formations; and evaluate biological and microbiological effects of CO_2 disposal in ocean.

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NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

06/2002

SORBENT AND CATALYST PREPARATION FACILITIES

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Capabilities

The National Energy Technology Laboratory (NETL) has facilities for the small scale preparation of sorbents/catalysts suitable for fixed, moving and fluid bed reactor applications. Equipment is also available for ASTM attrition tests, crush measurements and particle size analysis.

Mixer Pelletizer

- Mixing of different solid powders
- Agglomeration of solid materials for the preparation of pellets with 1-6 mm diameter, suitable for fixed bed reactor tests.
- 5 lbs batch production

Rotary Vacuum Evaporator

- Wet impregnation of porous substrates
- Batch production up to 2 lbs
- Particle size up to 1 cm in diameter

Lab-Scale Spray Dryer

- Semi-continuous production up to 1 lbs
- Particle sizes range from 40 to 100 microns in diameter
- Suitable for transport/fluid bed reactor applications

Dome Extruder

- Continuous production up to 15 lbs
- Particle sizes range from 0.5 mm to 5 mm in diameter
- Extrudates suitable for fixed bed reactor applications

Particle Spheronizer/Marumerizer

- Semi-continuous production up to 15 lbs
- Particle sizes range from 0.5 mm to 6 mm in diameter
- Transforms pellets into spherical shape

NETL

Sorbent and Catalyst Preparation Facilities

Attrition Tester for Materials Suitable for Fluid Bed/ Transport Reactor Applications

- Standard Test Method for Determination of Attrition and Abrasion of Powdered Catalysts by Air Jets - ASTM D 5757-95
- Suitable for particles with sizes less than 500 microns

Attrition Tester for Materials Suitable for Moving/ Fixed Bed Reactor Applications

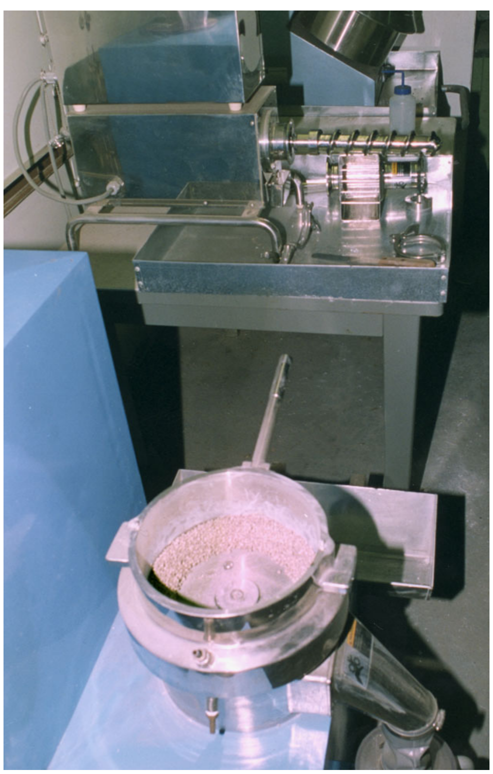
- Standard Test Method for Attrition and Abrasion of Catalysts and Catalyst Carriers - ASTM D 4058-92
- Suitable for particle sizes greater than 1 mm

Crush Strength Measurements

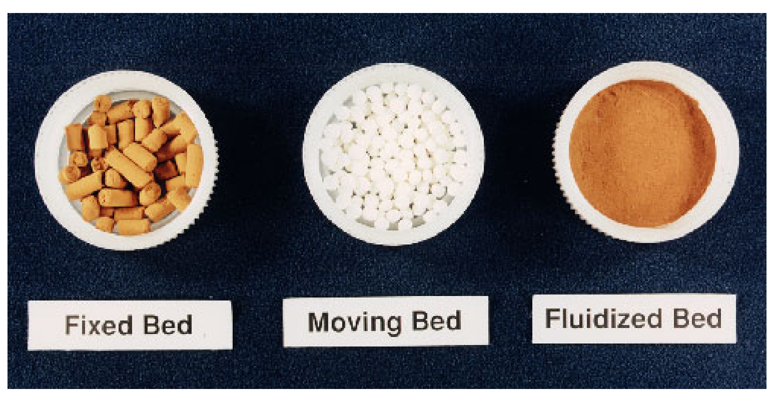
- Measurement of force necessary to break pellets using a push-pull gauge
- Suitable for mechanical strength measurements for materials used in fixed/moving bed reactor applications

Particle Size Analysis

- ASTM sieves for particles larger than 300 microns
- Coulter counter for water insoluble particles smaller than 300 microns
- API aerosizer for water soluble particles smaller than 300 microns



Sorbent/Catalyst Preparation Facilities



Sorbents

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National Energy Technology Laboratory

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Advanced Analytical Instrumentation and Facilities for In Situ Reaction Studies

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Capabilities

Various types of analytical instrumentation to conduct standard chemical/ physical characterizations and to study in-situ gas-solid reactions are available at the National Energy Technology Laboratory. These systems have unique capabilities to study in-situ gas/solid reactions at high temperature and/or high pressure. The systems can be utilized to determine reaction mechanisms, the extent of reactions and reaction kinetics. Analytical instrumentation includes both surface and bulk analysis techniques.

Thermogravimetric Analysis (TGA) Systems

- Determination of both the extent of gas/solid reactions and chemical kinetics
- High temperature and high pressure capabilities

Fourier Transform Infrared Spectroscopy (FTIR) with High Temperature Diffuse Reflectance Accessory/Gas Exposure Cell

- Capability to study reaction mechanisms by identifying intermediates and reaction products formed in-situ during gas/solid reactions.
- Chemical characterization and structural changes of materials.

Scanning Electron Microscopy/X-Ray Microanalysis

- Determination of elemental composition and distribution
- Determination of surface morphology of materials at various magnifications through secondary electron and backscatter electron image acquisition
- Image processing and analysis
- Insitu analysis at high temperature
- Gas exposure capabilities to study gas/solid reactions
- Multi-sample analysis capabilities

X-Ray Photoelectron and Auger Electron Spectroscopy

- Determination of surface elemental composition and oxidation states of solid materials
- Insitu analysis at high temperatures
- Gas exposure capabilities to study gas/solid reactions
- Multi-sample analysis capabilities

Atomic Force Microscope

- Analysis at both room temperature and high temperature
- Gas exposure capabilities

NETL

Advanced Analytical Instrumentation and Facilities for In Situ Reaction Studies

Other Analytical Capabilities for Physical and Chemical Characterization

Physical Characterization

- Particle Size Analyzer
- BET Surface Area & Pore Volume Analyzer
- Helium Density Analyzer
- Viscometers
- Specific Gravity Meter
- LECO Calorimeter

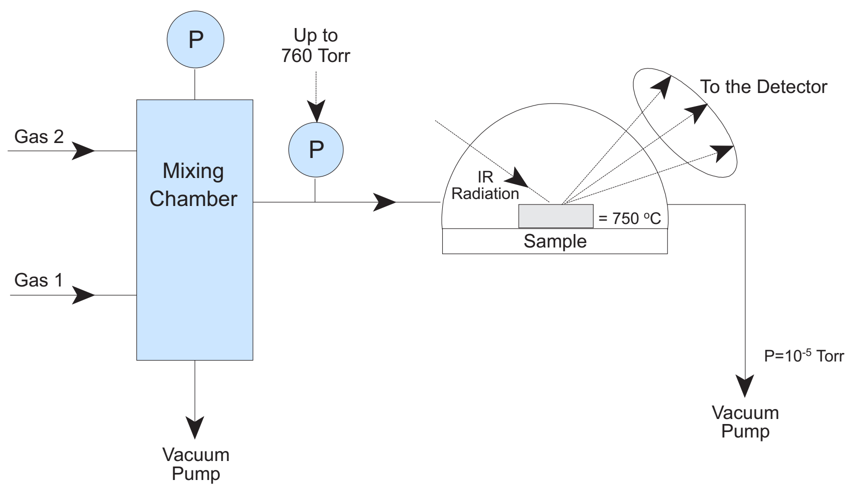
Reaction Studies

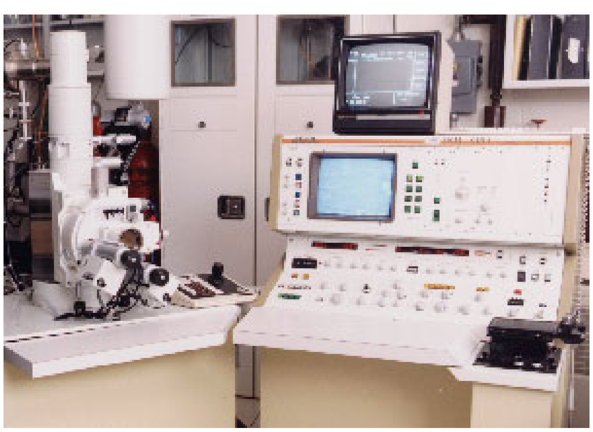
- Volumetric Absorption Apparatus
- Micro Reactor

Chemical Analysis

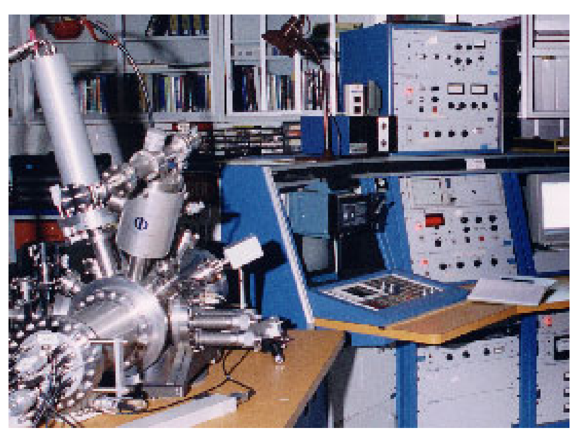
- X-ray Florescence
- Atomic Absorption Spectroscopy
- C, H, N Analyzer
- LECO Sulfur Analyzer
- Moisture, Ash & Volatile Matter Analyzer
- Gas Chromatography
- Nuclear Magnetic Resonance
- Mass Spectroscopy
- Inductively Coupled Plasma Spectroscopy

Diffuse Reflectance FTIR





Scanning Electron Microscopy



X-Ray Photo Electron and Auger Electron Spectroscopy

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Small-scale Facilities for Air Pollution Research

Capabilities

NETL is conducting research on the cleanup of flue gas produced by combustion of fossil fuels. This effort directly supports the goal of the Advanced Research and Environmental Technology Program to ensure continuing utilization of coal in an environmentally and economically acceptable manner. Novel technologies are being developed that can abate the air pollutants found in flue gas, such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), hazardous air pollutants (also referred to as air toxics) and fine particulates, and carbon dioxide (CO_2).

Research at NETL has focused on: (1) investigating air toxics produced by burning various coals, with a particular emphasis on the speciation of mercury and the control of the various mercury species; (2) dry, regenerable sorbent processes that use a metal-oxide sorbent to simultaneously remove SO_2 and NO_X; (3) catalysts for selective catalytic reduction (SCR)-type NO_X control; and (4) the capture of CO_2 removed from flue gas produced by fossil fuel combustion.

Examples of results that can be obtained in NETL's various small-scale reactor facilities include:

- Using a thermogravimetric analyzer and a microbalance to investigate adsorption or regeneration kinetics of dry, regenerable sorbents used to remove CO_2, SO_2, and NO_X from simulated flue gas. The large flow of gas over the small charge of sorbent (~ 50 mg) approximates a differential reactor, facilitating the interpretation of the kinetics by changes in weight.
- Using packed-bed reactors to screen sorbents or sorbent/catalysts for their reactivity toward the removal of certain gaseous pollutants. Continuous emissions monitors that can analyze for the various gas constituents at the reactor exit follow the behavior of the substance of interest.
- Coupling continuous analysis (atomic fluorescence spectrophotometer) of a difficult-to-measure gaseous pollutant (mercury) with a reactor scheme to screen novel sorbents for the removal of mercury from flue gas.
- Using unique schemes to investigate CO_2 capture: a bench-scale, packed-column scrubbing apparatus to study improved efficiency for wet chemical scrubbing of CO_2 from flue gas.

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Website

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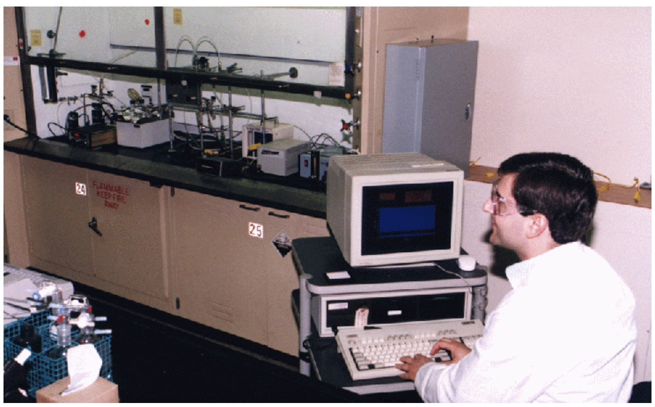
Small-scale Facilities for Air Pollution Research

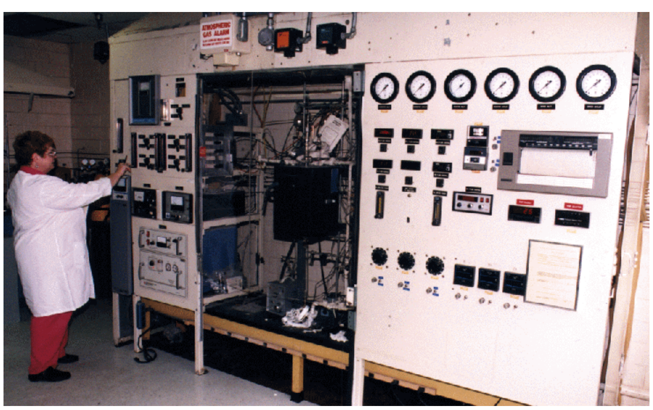
Opportunities

- Develop kinetic expressions for various gas-solid reactions.
- Screen various sorbents for removal of specific pollutants from flue gas.
- Characterize catalytic and non-catalytic gas-solid reaction systems by establishing experimental databases.
- Evaluate dry and wet scrubbing techniques for the capture of greenhouse gases.
- Work with industry using the various NETL facilities.

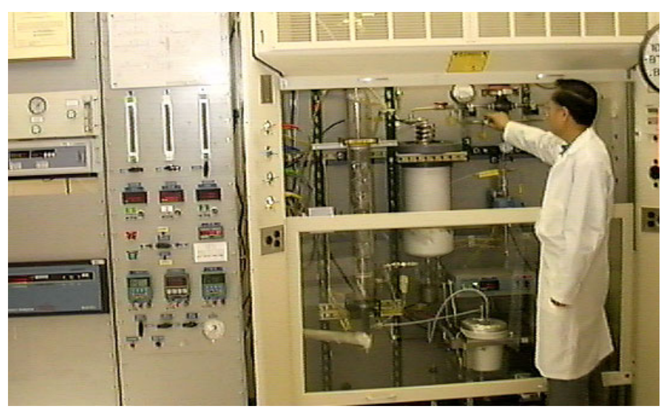


Data Acquisition System
Linked to Mercury Analyzer

Solid Sample Being Loaded Into
Thermogravimetric Analyzer



Packed-Bed Reactor Setup



Packed-Column Scrubbing Apparatus

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Sequestration

02/2003

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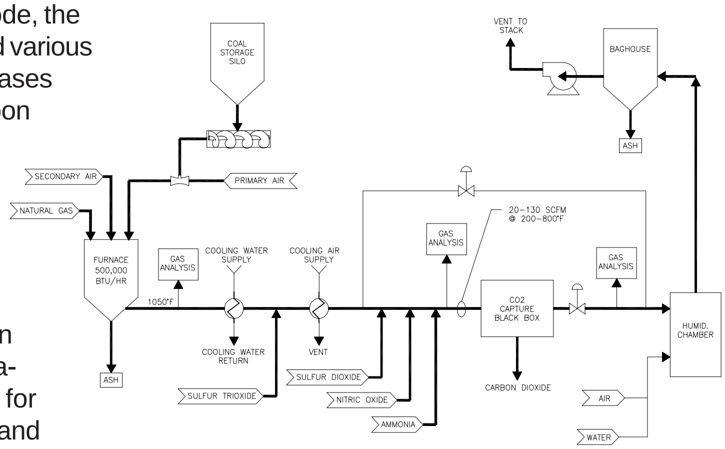
Modular Carbon Dioxide Capture Facility

Capabilities

Carbon Sequestration is rapidly becoming accepted as a viable option to reduce the amount of carbon dioxide (CO_2) emitted from large point sources, while continuing to use our Nation's fossil fuels to produce affordable, clean energy. As a major step in a carbon sequestration scenario (storage being the other), the capture or separation of carbon dioxide represents a significant cost and energy penalty in the overall sequestration process. To accelerate the development of low-cost capture and separation technologies, NETL is implementing the design and construction of a modular, flexible CO_2 capture test facility. The facility will be able to test new capture technologies on coal combustion flue gas and, additionally, on process gas from advanced fossil-fuel conversion systems, such as coal gasification. Ultimately, a database for a particular capture technology will provide experimental information from which further engineering scale-up decisions can be formulated.

In the flue gas mode, the Modular Carbon Dioxide Capture Facility (MCCF) will mimic coal-fired combustion processes that produce electricity. The combustor can be fired with natural gas, coal, or a combination of the two; coal-burning of approximately 40 pounds of pulverized coal per hour results in a flue gas (110-scfm) laden with various pollutants. The versatility of a "black-box" design will permit the incorporation of a particular capture/separation technology anywhere along the flue gas path. If regeneration of the capture medium is required as part of the capture/separation process, this step can be readily integrated into the system.

In a fuel gas mode, the MCCF will blend various high pressure gases (hydrogen, carbon monoxide, water, carbon dioxide, and minor components) to simulate the gas composition found in gasification processes, for example IGCC and Vision 21 plants.



CO_2 Capture Facility – Flue Gas

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Department of Energy • United States of America

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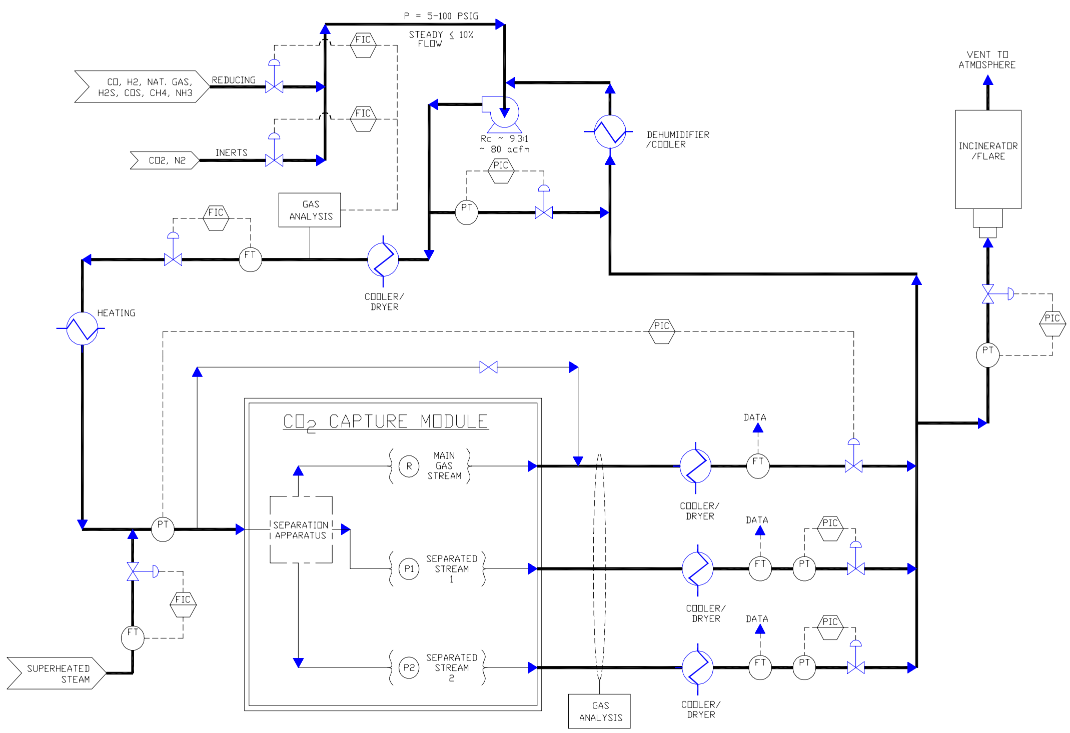
Again, a versatile design will permit installation of a capture technology, possibly including regeneration, along the fuel gas flow network.

By providing a means to evaluate the most promising capture/separation CO_2-abatement processes, the MCCF will help DOE meet its goal of developing point source cleanup systems that are more efficient, cleaner, and less costly than the current established techniques proposed for implementation in today's power generation plants.

Opportunities

- The MCCF has evolved as a multipurpose, versatile research facility.
- Performance of a particular carbon dioxide-abatement process can be optimized in the MCCF to help achieve the extremely high emissions-control goals of the DOE Carbon Sequestration program. Operational performance standards for CO_2 capture will thus be established.
- The MCCF provides the ability to test capture and separation concepts on process streams that simulate advanced energy conversion systems.
- Side-by-side comparison of advanced capture and separation concepts can be conducted.
- The MCCF can be used to investigate the impact of gaseous components (SO_2, NO_x, H_2S, particulates, and/or air toxics emissions) and other parameters on the particular technology.
- The MCCF offers industry and other sequestration stakeholders the opportunity to further develop CO_2 capture/separation technologies through cooperative ventures with the government (NETL). Collaborations with CO_2 capture technology developers will be sought.



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Capture of CO_2

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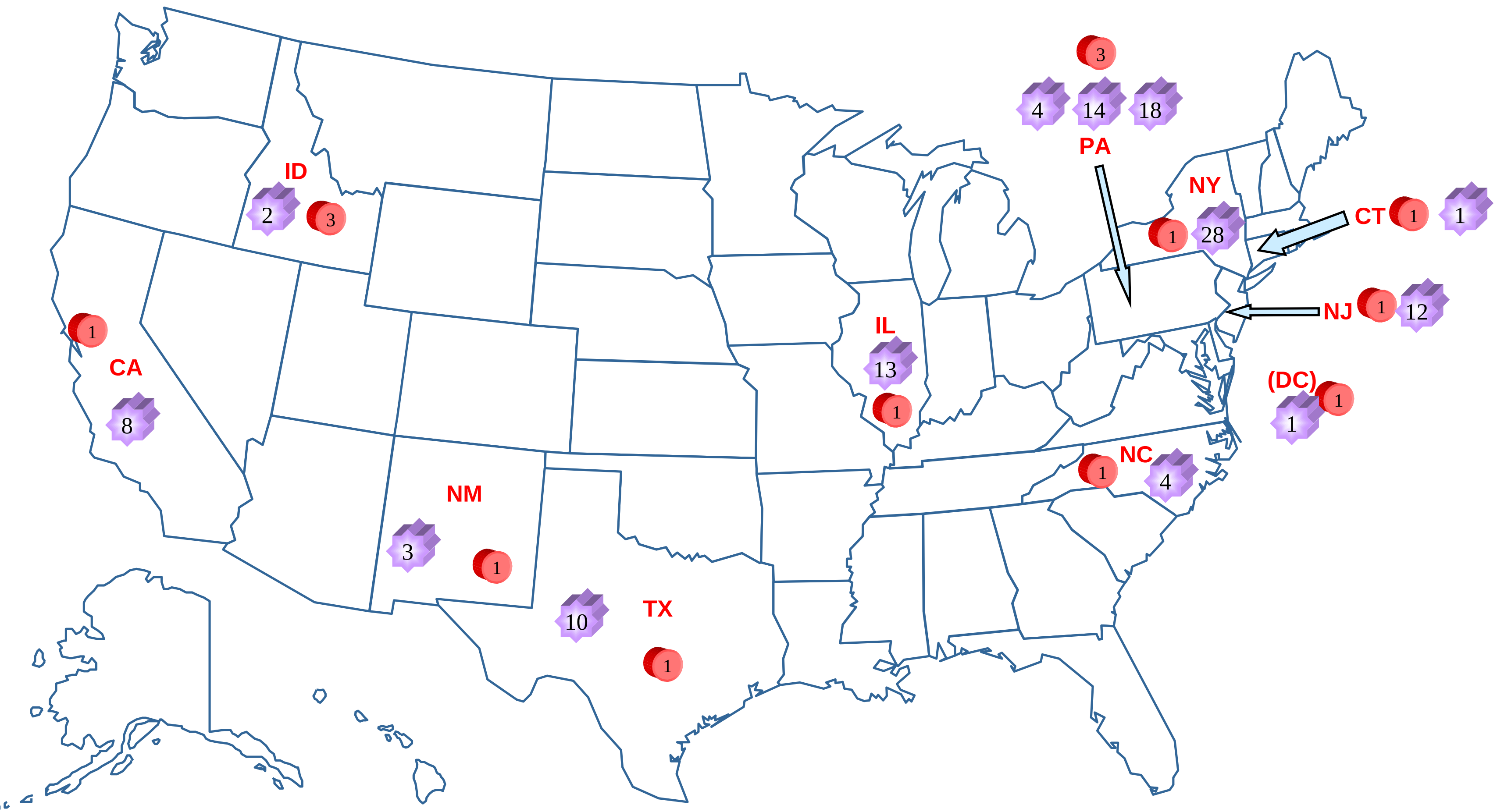
Capture of CO_2 Projects

LEGEND
Number of Capture of CO_2 Projects
Congressional District



*Includes BP. Doesn't include NETL

3/27/03

Capture of CO_2 Congressional Districts List

Project Title	Primary Contractor	Congressional District
Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO_2 Capture and Sequestration	Praxair, Inc.	NY28
CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream	Nexant	CA08
A Collaborative Project to Develop Technology for Capture and Storage of CO_2 from Large Combustion Sources	BP Corporation	DC01
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents	Research Triangle Institute	NC04
CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2	Media and Process Technology Inc.	PA04
CO_2 Separation Using a Thermally Optimized Membrane	INEEL	ID02
CO_2 Separation Using a Thermally Optimized Membrane	LANL	NM03
CO_2 Capture for PC-Boiler Using Flue-gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options	ANL	IL13
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers	ALSTOM Power, Inc.	CT01
Carbon Dioxide Capture by Absorption with Potassium Carbonate	University of Texas at Austin	TX10
An Integrated Modeling Framework for Carbon Management Technologies	Carnegie Mellon University	PA14
Zero Emissions Power Plants Using SOFCs and Oxygen Transport Membranes	Siemens Westinghouse Power Corp.	PA18
Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO_2	Princeton University	NJ12
Methodology for Conducting Probabilistic Risk Assessments of CO_2 Storage (BP Project)	INEEL (BP)	ID02

(NETL projects not included)

Capture of CO_2

Technology Target

- Complete pilot plant testing of precombustion decarbonylation systems
- Complete pilot plant testing of oxy fuel concept
- Complete pilot plant testing of promising post-combustion technology
- Cost-share power plant retrofit with advanced CO_2 capture technology

Commercialization

Outcomes

- Efficient low-cost electricity and hydrogen production with low GHG emissions
- Commercially viable options for retrofit/repower of existing plants to reduce CO_2 emissions

Open Category DOE $0.92M / Shared $0.23M

$ CMU - $0.717M (00-03) - Modeling framework for carbon management
$ Princeton Univ - $0.202M (02-03) - develop analytic and simulation tools for system design issues and economics

Pre Combustion
- Decarbonization
  - $ Advanced sorbents
  - $ Hybrid sorbent/membrane systems

DOE $5.7M / Shared $0.0M
$ Bechtel - $5.2M (99-05) - CO_2 Hydrate process for gas separation
$ NETL - $0.5M (02-03) - Sorbent development for CO_2 separation and removal
$ See Membrane Research section for membrane projects

BP DOE $0.88M / Shared $0.88M
$ Air Products - $0.5M (02-03) - Sorption Enhanced Shift reaction with CO_2 Removal
$ Flour Daniel - $0.38M (02-03) - Process design (with and without CO_2 recovery on gas separation options)
$ See Membrane Research section for membrane projects

Oxyfuel
$ O_2 - selective membranes
$ Advanced cooling cycles
$ Compact boiler

DOE $5.7M / Shared $2.2M
$ Praxair - $4.1M (01-05) - Advanced oxy-fuel boilers and process heaters
$ Alstom Power - $1.6M (01-04) - Oxygen firing in CFB boiler
$ See Membrane Research section for membrane projects

BP DOE $0.2M / Shared $0.2M
$ Haldor Topsoe, Inc. - $0.2M (2002) - Autothermal Reformer study
$ See Membrane Research section for membrane projects

Post Combustion
$ Chemical and physical sorbents
$ Hybrid sorbent/membrane system
$ Gas/liquid contractors

DOE $3.8M / Shared $0.51M
$ RTI - $0.81M (00-03) - Dry regenerable CO_2 sorbents
$ ANL - $0.5M (97-02) - Retrofit flue-gas recirculation equipment
$ NETL- $0.28M (02-03) - CO_2 scrubbing with regenerable sorbents
$ NETL - $0.21M (02-03) - Novel amine-enriched sorbents
$ NETL - $0.4M (02-03) - SO_2 & NOx and CO_2 removal with aqua ammonia
$ NETL - $1.1M (02-03) - Modular CO_2 Capture facility
$ UT Austin - $0.46M (02-03) - Absorption with K_2CO_3/Piperazine

BP DOE $0.2M / Shared $0.2M
$ SRI - $0.2M (02-03) - Design nano-porous sorbents for CO_2 removal

UCR DOE $0.07M / Shared $0.008M
$ Univ. of Cincinnati - $0.05M (01-02) - Develop alkali metals based sorbents for high temperature CO_2 removal

-HBCU
$ Hampton Univ. - $0.02M (02-03) - Enhanced absorption by adding organic phase into gas-aqueous phase system

Membrane Research - *Gas Separation*

Summary
Total = 26 projects
(SEQ = 11)
Total DOE cost = $15M
($2.25M Shared)
Total Seq program cost = 2.6M ($0.18M)

→ Solicitation for POC testing

→ **Technology Target**
$ Establish pilot-scale test capability
$ Complete pilot-plant testing
$ Initiate cost-shared precommercial test

→ **Commercialization** →

Cost Savings
25% savings in shift conversion
1% savings in COE

BP Carbon Capture Project
DOE $1.1M / Shared $1.1M

$ **ECN** - $0.45M (02-04) - Silica membrane for H_2
$ **Flour Daniel** - $0.2M (02-03) } S-tolerant WGS reactor
$ **McDermott** - $0.16M (02-03) } Process development
$ **Univ. of Cincinnati** - $0.16M (02-03) - Zeolite membrane for WGS
$ **Eltron** - $0.1M (2002) - S-tolerant H_2 transport membrane
-Pervoskite and Al_2O_3 with WGS catalyst
$ **CSM** - $0.06M (01-02) - S-tolerant WGS using Pd-Cu

$ CO_2 Selective Membrane

$ Membranes that both shift CO & separate CO_2/H_2

Gasification Projects
DOE $8.5M / Shared $0.8M
-H_2 Separation

$ **ANL** - $2.8M (98-02) - MDCM
$ **ITN** - $2.6M (01-04) - ICM
$ **Eltron** - $1.7M (00-03) - DCM
$ **ORNL** - $0.7M (99-02) - Design model
$ **INEEL** - $0.5 (01-03) - CM
$ **NETL** - $0.19 (02-03) - H_2 separation membranes

Sequestration Project
DOE $2.6M / Shared $0.18M

$ **LANL** - $1.2M (00-03) - Polymeric metallic membrane for CO_2 separation
$ **Media and Process Tech** - $0.72M (00-03) - Hydrotalcite membrane for CO_2 recovery
$ **INEEL** - $0.18M (00-03) - Polymer membrane for CO_2 separation
$ **NETL** - $0.185M (02-03) - Hybrid membranes for CO_2 Removal
$ **Siemens Westinghouse** - $0.28M (2002) - V21 CO_2 capture

UCR/AR
DOE $2.8M / Shared $0.17M

$ **ORNL** - $0.67M (01-02) - H_2 separation alumina membrane
$ **Media & Process** - $0.6M (99-02) - H_2 separation SiC base membrane
$ **LANL** - $0.4M (98-02) - H_2 from Pd membrane
$ **Tuft Univ.** - $0.2M (00-02) - H_2 separation catalyst/ membrane
$ **NC State** - $0.2M (99-02) - Metal ceramic composite membrane-H_2
$ **Colorado School** - $0.2M (99-02) - S-resistant Pd-Cu composite-H_2
$ **Univ. of Cincinnati** - $0.2M (00-03) - Proton conducting membrane permeable to H_2
$ **SUNY** - $0.2M (99-02) - Catalyst/inorganic membrane for H_2
$ **CALTECH** - $0.14M (00-02) - MH_2 separation composite membrane

Capture of CO_2 Project Fact Sheet List

Project Title	Primary Contractor	Fact Sheet Listing
Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO_2 Capture and Sequestration	Praxair, Inc.	C-6
CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream	Nexant	C-8
A Collaborative Project to Develop Technology for Capture and Storage of CO_2 from Large Combustion Sources	BP Corporation	C-10
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents	Research Triangle Institute	C-12
CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2	Media and Process Technology Inc.	C-16
CO_2 Separation Using a Thermally Optimized Membrane	LANL & INEEL	C-18
CO_2 Capture for PC-Boiler Using Flue-gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options	ANL	C-20
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers	ALSTOM Power, Inc.	C-22
Carbon Dioxide Capture by Absorption with Potassium Carbonate*	University of Texas at Austin	C-24
An Integrated Modeling Framework for Carbon Management Technologies*	Carnegie Mellon University	C-26
Zero Emissions Power Plants Using SOFCs and Oxygen Transport Membranes*	Siemens Westinghouse Power Corp. - Pittsburgh	C-28
Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO_2*	Princeton University	C-30
Sorbent Development for Carbon Dioxide Separation and Removal – PSA & TSA	NETL	C-32
CO_2 Scrubbing with Regenerable Sorbent*	NETL	C-34
Novel Amine-Enriched Sorbents*	NETL	C-36
NO_2 & NOx and CO_2 Removal with Aqua Ammonia*	NETL	C-38
Modular CO_2 Capture Facility*	NETL	C-40

(BP and UCR projects not included)

* Factsheet Under Development

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PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

09/2002

ADVANCED OXYFUEL BOILERS AND PROCESS HEATERS FOR COST EFFECTIVE CO_2 CAPTURE AND SEQUESTRATION

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Background

Reducing CO_2 from large stationary combustion systems has been targeted as a cost efficient means of reducing the emission of greenhouse gases from fossil fuel combustion systems. A number of concepts exist or have been proposed to reduce emissions, including fuel switching, efficiency improvements, CO_2 capture from conventional flue gas streams, and oxy-fuel fired systems with CO_2 capture. Switching fuels from coal to lower carbon fuels such as natural gas can reduce emissions, but severely restricts the nation's fuel flexibility and underutilizes the most abundant natural resource in the United States. Enhancing site efficiency by building natural gas combined cycle plants or making efficiency improving plant modifications can also significantly reduce emissions of greenhouse gases. However, these options simply do not provide enough reduction in emissions to mitigate the growing problem of global warming.

One economical solution to overcome these problems is to switch to oxy-fuel combustion. The use of oxygen in place of air results in a much lower volume of flue gas, which enhances thermal efficiency, thereby lowering CO_2 emissions. This four-year project will advance the integration of oxygen transport membranes (OTM) into oxyfired boilers from the bench scale to the point-of-readiness for engineering scaleup. The development of this novel boiler will require both Praxir's expertise in OTM development and oxy-fuel combustion and the experience of Alstom Power in boiler development and manufacturing. These highly efficient boilers, through incorporation of lower cost OTM oxygen generation technology, can economically provide a significant portion of the required reductions in greenhouse gases.

Primary Project Goal

The object of this project is to develop and demonstrate the integration of a novel ceramic oxygen transport membrane (OTM) with the combustion process to enhance boiler efficiency and carbon dioxide recovery.

NETL

ADVANCED OXYFUEL BOILERS AND PROCESS HEATERS FOR COST EFFECTIVE CO_2 CAPTURE AND SEQUESTRATION

Objectives

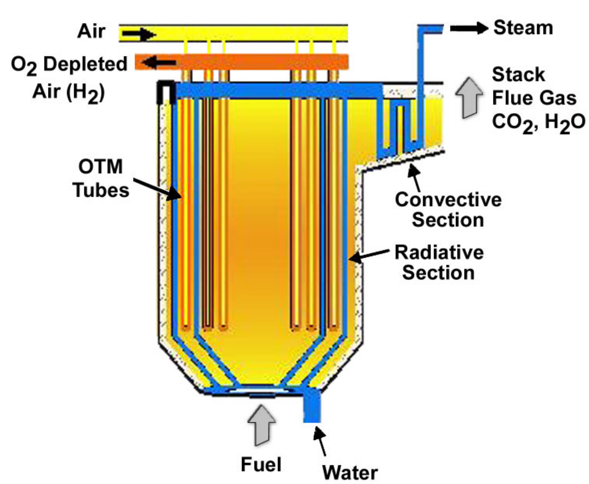
- Identify the optimal design based on technical performance; identify and demonstrate the most promising OTM materials for the integrated system; and develop a conceptual design for a laboratory scale boiler simulator.
- Perform economic analyses throughout the program to ensure the novel boiler will bring economic value to both the industrial customers and to the participating companies.
- Complete project by December 2005.

Accomplishments

A ceramic membrane and seal assembly have been developed for thermal integration between the high temperature membrane and the combustion process. Alstom Power has initiated modeling studies to understand and predict the combustion characteristics of oxy-fuel technology. Current efforts are focusing on laboratory scale evaluations for integration of OTM with the combustion process.

Benefits

The development of a novel oxy-fuel boiler will significantly reduce the complexity of CO_2 capture, drastically reduce the cost of carbon sequestration, and offer increased thermal efficiency and reduced pollution emissions. This highly efficient boiler will economically provide a significant portion of the required reductions in greenhouse gases. Gasification plants which integrate OTM technology will have higher efficiency, lower cost of electricity, and lower emissions of pollutants compared to using a conventional cryogenic air separation unit.



Praxair Advanced Boiler

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PARTNERS

Praxair

Alstom Power

COST

Total Project Value:	$5,836,487
DOE/Non-DOE Share:	$4,085,537 / $1,750,950

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

09/2002

CO_2 HYDRATE PROCESS FOR GAS SEPARATION FROM A SHIFTED SYNTHESIS GAS STREAM

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Background

One approach to decarbonizing coal is to gasify it to form fuel gas consisting predominately of carbon monoxide and hydrogen. This fuel gas is sent to a shift conversion reactor where carbon monoxide reacts with steam to produce carbon dioxide and hydrogen. After scrubbing the carbon dioxide from the fuel, an almost pure hydrogen stream is left which can be burned in a gas turbine or used to power a fuel cell with essentially zero emissions. However, for this approach to be practical, it will require an economical means of separating carbon dioxide from mixed gas streams. Since viable options for sequestration or reuse of carbon dioxide are projected to involve transport through pipelines and/or direct injection of high pressure carbon dioxide into various repositories, a process that can separate carbon dioxide at high pressures and minimize recompression costs will offer distinct advantages. This project addresses the issue of carbon dioxide separation from shifted synthesis gas at elevated pressures.

The project is concerned with development of the low temperature SIMTECHE process. This process utilizes the formation of carbon dioxide hydrates to remove CO_2 from a gas stream. Many people are familiar with methane hydrates but are unaware that, under the proper conditions, CO_2 forms similar hydrates. In Phase 1, a conceptual process flow scheme was developed. The thermodynamic limits of such a process were confirmed by equilibrium hydrate formation experiments for shifted synthesis gas compositions. Performance projections were then made for a few selected process configurations, and encouraging preliminary economics were developed.

Primary Project Goal

The goal of this project is to construct and operate a pilot-scale unit utilizing the hydrate process for CO_2 separation.

NETL

CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream

Objectives

The objective of this phase of the program is to carry out further laboratory-scale tests on the CO_2 hydrate concept, consisting of research and development studies, as well as component testing. Previously developed process modelling will be extended to the latest proposed concept for the SIMTECHE process. Another objective is to evaluate the ultimate reduction in carbon dioxide concentration that can be achieved and to assess the potential negative influence of H_2S and CH_4 on the process. The third phase will further establish the pilot-scale unit and provide detailed design and operating data.

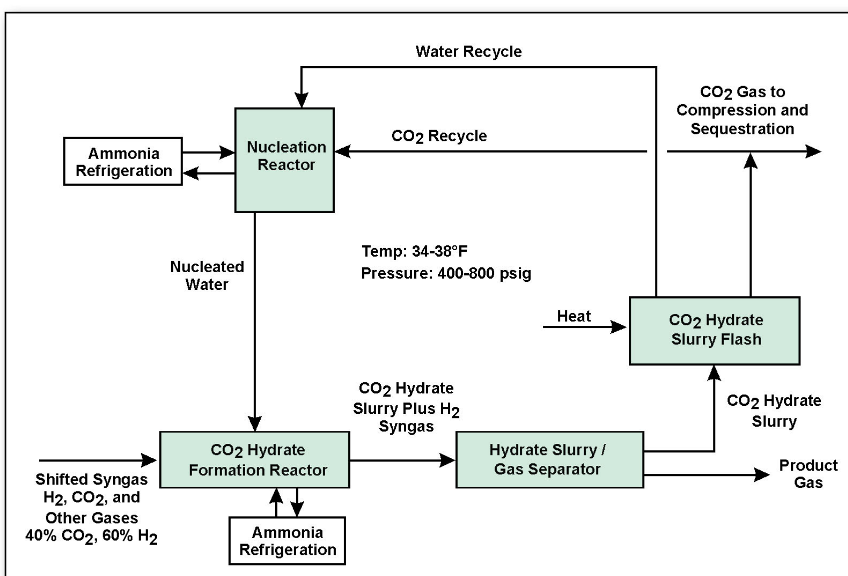
Accomplishments

A bench-scale flow system for the continuous production of carbon dioxide hydrates was assembled, and operational issues associated with continuous hydrate production were resolved. The technical feasibility of the SIMTECHE process was thereby demonstrated. The enhancement of carbon dioxide hydrate formation and separation by the presence of gaseous and/or liquid promoters was also demonstrated in the laboratory.

Benefits

The hydrate process will provide a high pressure/low temperature system for separating CO_2 from shifted synthesis gas in an economical manner. The process can be adapted to an existing gasification power plant for CO_2 separation in the production of synthesis gas.

Overall, the process will result in a residual concentrated stream of hydrogen capable of fueling zero-emission power plants of the future and a concentrated CO_2 stream available for use or sequestration.



Conceptual Process Block Flow Diagram of a CO_2 Hydrate Process

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PARTNERS

Nexant

Los Alamos National Laboratory (LANL)

IPSI LLC

SIMTECHE

COST

Total Project Value: $9,076,621

DOE/Non-DOE Share: $9,076,621 / $0

CUSTOMER SERVICE

800-553-7681

WEBSITE

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PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

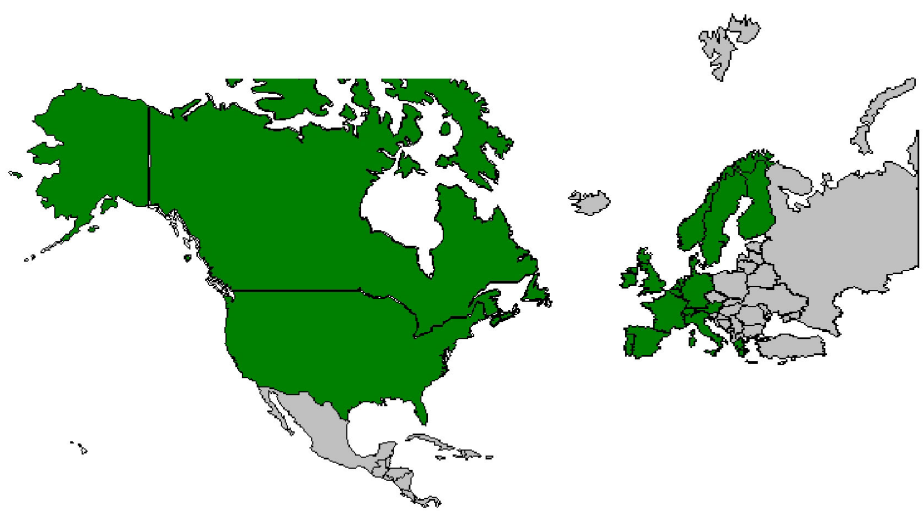
Sequestration

09/2002

CARBON CAPTURE PROJECT: COLLABORATIVE TECHNOLOGY DEVELOPMENT PROJECT FOR NEXT GENERATION CO_2 SEPARATION, CAPTURE AND GEOLOGIC STORAGE

Background

DOE has joined with eight major international energy companies to sponsor the Carbon Capture Project (CCP) with the goal of developing breakthrough technologies aimed at substantially reducing the cost of CO_2 capture and geologic storage. The CCP consortium is operated by BP and its members include ChevronTexaco, ENI, Norsk Hydro, PanCanadian, Shell, Statoil, and Suncor. In addition to the U.S. program, the CCP is comprised of separate, but complimentary projects which are also being sponsored by the European Union, and Norway. The total value of the Carbon Capture Project, including international components, is $25 million.



Global participation of International Leading Energy Companies

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Participating Phase I Technology Providers

Air Products & Chemicals, Inc.

Colorado School of Mines

Eltron Research Corporation

Energy Resource Centre of the Netherlands (ECN)

Fluor Daniel, Inc.

Idaho National Engineering & Environmental Laboratory

Lawrence Berkeley National Laboratory

Lawrence Livermore National Laboratory

McDermott Technology, Inc.

Netherlands Institute of Applied Geosciences

Oakridge National Laboratory

Scientific Monitor

SINTEF

Stanford University

Stanford Research Institute

TDA Research, Inc.

Texas Tech University

Tie-Line Technology

University of Cincinnati

Utah State University

The project schedule spans a 3-year period and is divided into two phases. Phase 1 represents the initial technology development period in which various promising avenues of R&D are pursued. Phase 2 will involve reprioritizing the R&D activities based on Phase 1 findings and then continuing with development of the most promising technologies.

Objectives

The strategic objective of the proposed project is to work with selected technology providers to develop new, breakthrough technologies, to the proof-of-feasibility stage, to reduce the cost of CO_2 separation, capture, transportation and sequestration from flue gases by one-half over today's best available technology for existing facilities, and by three-quarters for new facilities, by the end of 2003. The tactical objectives of the project are to:

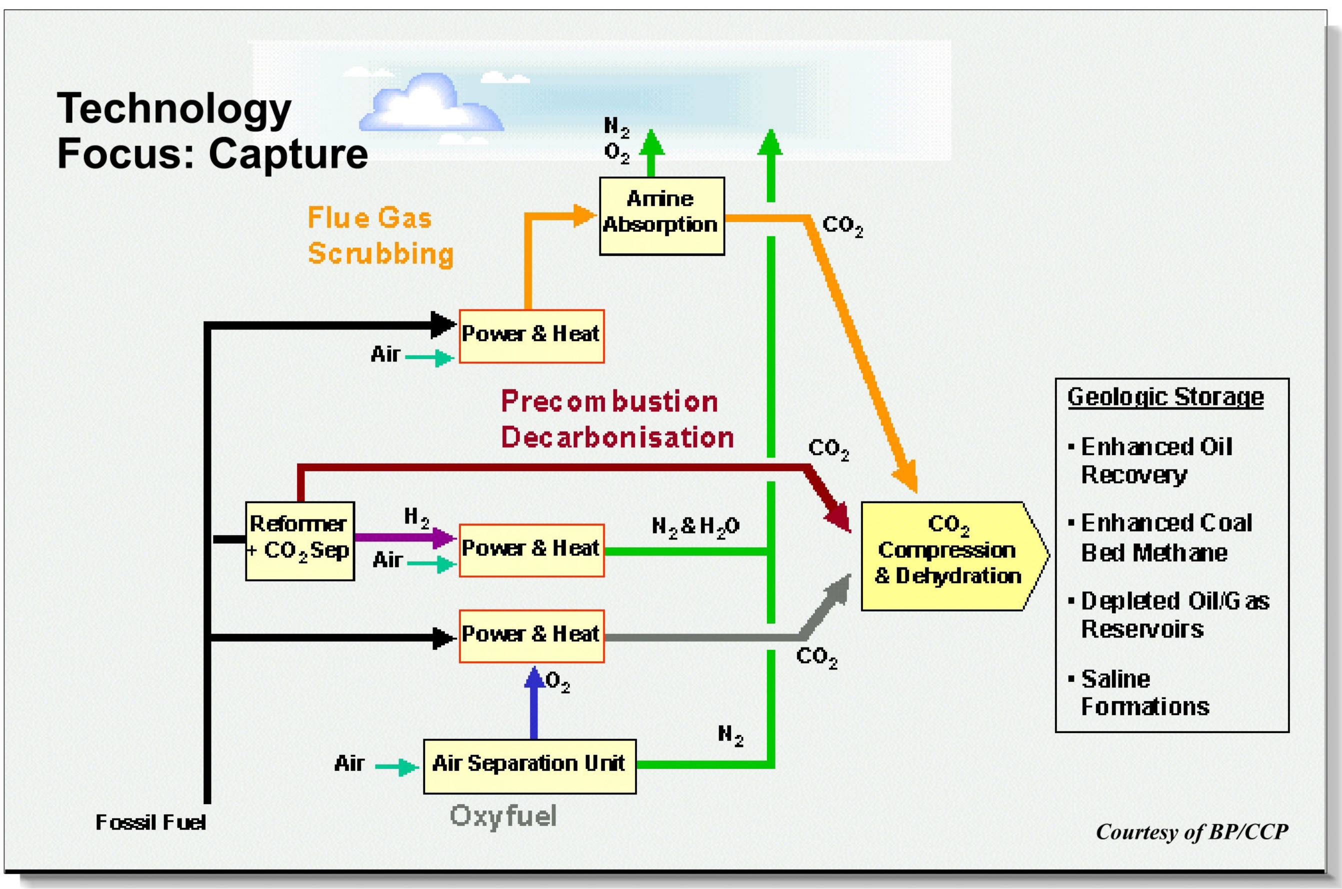
- Perform "benchtop" R&D (engineering studies, computer modeling, laboratory experiments) to prove the feasibility of advanced CO_2 separation and capture technologies, specifically targeting post-combustion methods, pre-combustion decarbonization, and oxyfuel.
- Develop guidelines for maximizing safe geologic sequestration, for measuring/verifying sequestration volumes, and for assessing and mitigating sequestration risks.
- Demonstrate to external stakeholder that CO_2 storage is safe, measurable, and verifiable.
- Develop technologies to the "proof of concept" stage by 2003/2004 and achieve at least one large-scale application by 2010

Benefits

The CCP team collectively accounts for approximately 32% of all oil and 17% of all gas production in the U.S., and 28% and 17% of oil and gas production respectively from OECD countries,. This team not only represents a significant market for the technologies to be developed, it is in the unique position of also operating and utilizing many of the geologic sinks needed to sequester the CO_2. These existing commercialization pathways will facilitate rapid industrial deployment of the new technologies developed under this project. Using conservative assumptions, the technology developed in the project could reduce the emissions of the CCP participants by 10 million tonnes of carbon per year (11 million tons per year). When applied more broadly in industry, the technology could reduce emissions by up to 140 million tonnes of carbon per year.

The potential scientific breakthroughs that could result from this project include:

- New solvents to reduce CO_2 separation costs.
- Improved CO_2 /H_2 absorption membranes.
- Integrated H_2 generation processes.
- Advanced oxyfuel boiler designs.
- An enhanced understanding of controls and requirements for geologically sequestering CO_2.



Flow diagram of various CO_2 capture and storage technologies

Carbon Capture Project: Collaborative Technology Development Project for Next Generation CO_2 Separation, Capture and Geologic Storage

PARTNERS

National Energy Technology Laboratory

ChevronTexaco

Norsk Hydro

Shell

Statoil

Suncor Energy

Pan Canadian

ENI

COST

Total Project Value:	$9,994,165
DOE/Non-DOE Share:	$4,995,000 / $4,999,165

In addition to reducing technology costs, domestic energy security will also benefit. The proposed project develops lower cost separation and capture technology, which when combined with value-added geologic sequestration opportunities (EOR and ECBM) provides industry with a market-driven mid-term option for reducing CO_2 emissions while continuing to use fossil fuels. Additional benefits include a significant increase in the production of domestic oil and natural gas which improves U.S. energy security. It is estimated that 12 billion barrels (1.9 billion m 3) of incremental oil and 31 Tcf (0.9 Tm 3) of incremental gas is technically recoverable via these processes. Although the technology will enhance viability of CO_2 EOR, the focus of the R&D will be on new technologies to maximize the amount of CO_2 stored and the assurance and verification of sequestered volumes.

Proj185.pmd

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

08/2002

CARBON DIOXIDE CAPTURE FROM FLUE GAS USING DRY REGENERABLE SORBENTS

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CUSTOMER SERVICE

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WEBSITE

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NETL

Background

Currently available commercial processes to remove CO_2 from waste gas streams are costly. Research Triangle Institute, working with Church and Dwight, Inc., is developing an innovative process for CO_2 capture that employs a dry, regenerable sorbent. The process is cyclic in that the sorbent first captures the CO_2, is regenerated to yield a concentrated stream of CO_2, and then recycled to the absorption/adsorption step. Although, the proposed process can be used to remove CO_2 from flue gas, it can also be used to capture CO_2 from gasification streams at high temperature.

Sorbents being investigated, primarily alkali carbonates, are converted to bicarbonates through reaction of carbon dioxide and water vapor. Sorbent regeneration produces a gas stream containing only CO_2 and water. The water may be separated out by condensation to produce a pure CO_2 stream for subsequent use or sequestration.

Primary Project Goal

The goal of this project is to develop a simple, inexpensive process to separate CO_2 as an essentially pure stream from a fossil fuel combustion system using a regenerable sorbent.

Objectives

To develop a technology that is

- Applicable to both coal and natural gas-based power plants.
- Applicable as a retrofit to existing plants, as well as to new power plants.
- Compatible with the operating conditions in current power plant configurations.
- Able to handle flue gas containing contaminants such as SO_2, HCl, particles, and possibly heavy metals, such as Hg.
- Relatively simple to operate.
- Significantly cheaper than currently available technologies.

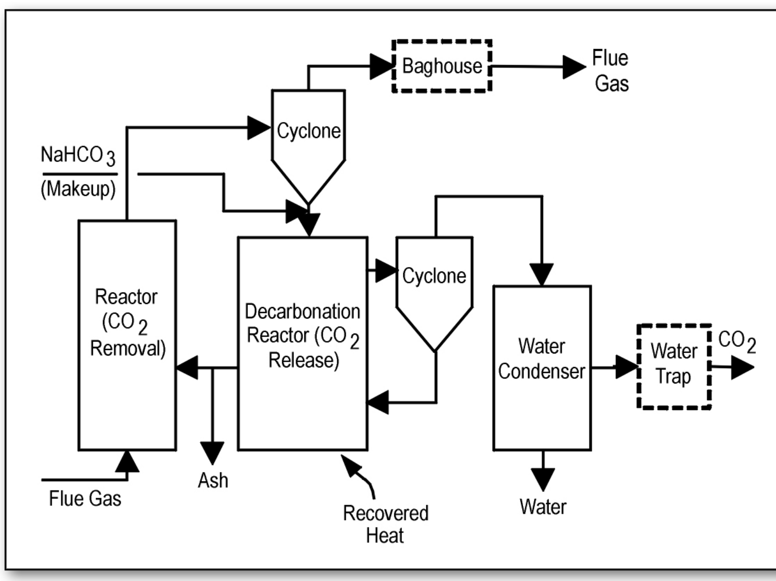
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents

Accomplishments

The sorbent material has been well characterized and analyzed for chemical composition. Testing has confirmed that the reaction rate and achievable CO_2 capacity of sodium carbonate decreases with increasing temperature and that the global rate of reaction of sodium carbonate to sodium bicarbonate increases with an increase in both CO_2 and H_2O concentrations. It has been shown that capture of 25% of the CO_2 will not require any additional power. Future efforts will be aimed at optimizing the process to capture additional CO_2 without requiring additional power.

Benefits

This technology will provide conventional pulverized-coal fired power plants, natural gas-fired combined cycle plants, and advanced power generation systems with a less costly process to remove CO_2 from the flue gas. The ability to operate a CO_2 removal system at higher temperatures is more efficient that low temperature systems.



Conceptual Transport Reactor System

This configuration is an attractive treatment option for flue gas from power plants employing wet FGD and for flue gas from natural gas-fired systems.

PARTNERS

RTI

Church and Dwight, Inc.

Louisiana State University

COST

Total Project Value: $1,050,889

DOE/Non-DOE Share: $812,285 / $238,604

Proj198.pmd

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

09/2002

CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2

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CUSTOMER SERVICE

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WEBSITE

Background

The water-gas-shift (WGS) reaction, $CO + H_2O \leftrightarrow H_2 + CO_2$, is used to increase the hydrogen content of synthesis gas. However, this reaction is equilibrium limited. One approach for overcoming this limitation is to carry out the reaction in a reactor with walls that are CO_2 permeable. This continuously removes CO_2 from the system and allows the reaction to continue.

This project involves the development of a technique for depositing hydrotalcite onto a ceramic membrane suitable for implementing the reactive separation concept with the WGS reaction in integrated gasification combined cycle (IGCC) systems. The membranes are being developed using available sol gel and chemical vapor deposition (CVD) preparation techniques. The hydrotalcite is permeable to CO_2 but plugs the pores, preventing passage of other gases. The hydrothermal and chemical stability in a simulated WGS reaction environment will be evaluated to confirm the inert material properties of the ceramic membrane. Then, a membrane reactor (MR) study will be conducted to demonstrate the benefit offered by this membrane. Finally, process feasibility will be demonstrated in a test module, and an economic evaluation will be performed to estimate the positive effect of using a WGS-MR in IGCC coal-fired power plants.

Primary Project Goal

The primary objective of this program is to develop a defect-free hydrotalcite membrane for selective CO_2 removal that will be effective in the water-gas-shift reaction environment, i.e., 300 to 600°C and in the presence of steam.

Objectives

- Conduct a screening study to select an optimal material for developing a membrane and determine the optimum operating conditions in terms of temperature and steam content of the gas for selective CO_2 removal (good thermal, hydrothermal and chemical stability).
- Fabrication of the desired membrane in tubular geometry and verification of the feasibility of CO_2 separation along with the conversion enhancement.

NETL

CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2

Partners

Media and Process Technology Inc.

University of Southern California

Cost

Total Project Value:	$900,000
DOE/Non-DOE Share:	$720,000 / $180,000

Accomplishments

Results from the TGA/MS studies show that the hydrotalcite material exhibits a high degree of CO_2 reversibility. Insignificant adsorption of water has been observed at higher temperatures (greater than 200ºC). Based on these results, the conclusion is that the hydrotalcite is an ideal candidate material for high temperature gas separations requiring hydrothermal stability.

Benefits

This combined shift reaction and CO_2 separation system project will produce a hydrogen rich gas which is at high pressure, high temperature and contains significant quantities of steam making it highly suitable for direct firing in a gas turbine with high efficiency. The use of an improved WGS-MR with CO_2 recovery capability is ideally suited to integration into the IGCC) power generation system. Thus, the hydrogen (high pressure and CO_2 -free) produced from the IGCC can be used either as a product for power generation via a turbine or a fuel cell, or as a reactant for fuels and chemicals production.

Proj195.pmd

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

09/2002

CO_2 SEPARATION USING A THERMALLY OPTIMIZED MEMBRANE

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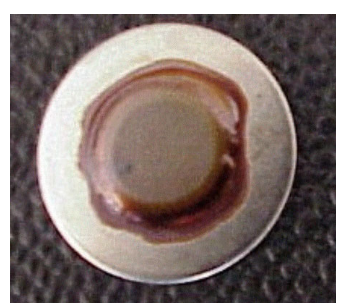
Background

The last decade has witnessed a dramatic increase in the use of polymer membranes as an effective, economic, and flexible tool for many commercial gas separations, including air separation, the recovery of hydrogen from nitrogen, carbon monoxide, and methane mixtures, and the removal of carbon dioxide from natural gas. In each of these applications, processes with high fluxes and excellent selectivities have relied on glassy polymer membranes, which separate gases based on both size and solubility differences. To date, however, this technology has focused on optimizing materials for near ambient conditions.

Los Alamos National Laboratory (LANL), in collaboration with Idaho National Energy and Engineering Laboratory (INEEL), will develop a high-temperature polymer membrane that will exhibit permselectivity for CO_2 an order of magnitude higher than current polymer membranes. The project will focus on the separation of CO_2/CH_4 and CO_2/N_2 gas pairs, which represent separations that are industrially and environmentally important. Capitalizing on the interplay between polymer structure and gas diffusion at temperatures between 100°C and 400°C will lead to structures with unprecedented stability and selectivity. By increasing the rigidity of the thermally stable polybenzimidazole (PBI) backbone and using semi-interpenetrating polymer networks, the researchers will inhibit interchain mobility and control diffusion pathways. This approach will lead to polymer membranes with tunable permeability, polymer modification and casting protocols. This approach will maintain high selectivity while allowing tuning permeability by increasing temperature. Industrial collaboration with Pall Corporation and Shell Oil Company provide the project with direct involvement of world leaders in membrane production and CO_2 separation, respectively.

Primary Project Goal

The purpose of this project is to develop polymeric-metallic membranes for carbon dioxide separation that operate under a broad range of industrially relevant conditions not accessible with present membrane units.



PBI coated metal

CO_2 SEPARATION USING A THERMALLY OPTIMIZED MEMBRANE

PARTNERS

Los Alamos National Laboratory

Idaho National Energy and Engineering Laboratory

Pall Corporation

Shell Oil Company

COST

Total Project Value: $1,400,360

DOE/Non-DOE Share: $1,400,360 / $0

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Objectives

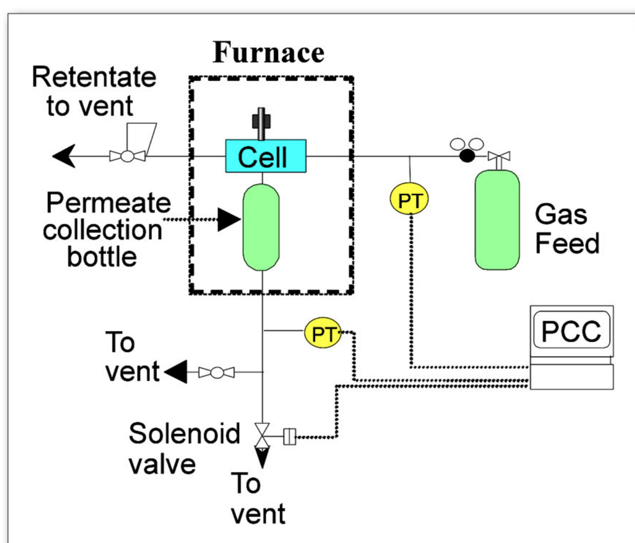
The major objective is the development of polymeric materials that achieve the important combination of high selectivity, high permeability, and mechanical stability at temperatures significantly above 25°C and pressures above 10 bar.

Accomplishments

Progress to date includes the first ever fabrication of a polymeric-metallic membrane that is selective from room temperature to 350°C. This achievement represents the highest demonstrated operating temperature at which a polymeric based membrane has successfully functioned. Additionally, the first polybenzamidizole silicate molecular composites have been generated. Finally, a technique has been developed that has enabled the first-ever simultaneous measurements of gas permeation and membrane compaction at elevated temperatures. This technique provides a unique approach to the optimization of long-term membrane performance under challenging operating conditions.

Benefits

The development of high temperature polymeric-metallic composite membranes for carbon dioxide separation at temperatures of 100-450°C and pressures of 10-150 bar will provide a pivotal achievement with both economic and environmental benefits. This technology could further reduce the cost of CO_2 sequestration by providing a CO_2 stream at higher pressures than existing technologies, thereby reducing compression costs significantly.



Membrane Testing Equipment

Proj194.pmd

Sequestration

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

10/2002

PRIMARY PARTNER

Argonne National Laboratory

DOE FUNDING PROFILE

DOE	$ 569,000
Non-DOE	$ 0

TOTAL ESTIMATED COST

DOE	$ 569,000

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CO_2 Capture for PC-Boiler Using Flue-Gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options

Background

Concerns over possible global climate changes due to increasing atmospheric concentrations of greenhouse gases, such as carbon dioxide, have led to a strong emphasis on the development of high-efficiency, coal-based energy systems, incorporating the recovery of CO_2 for sequestration or use. One approach is the use of oxygen fired combustion with flue gas recycle to maintain a normal temperature profile in the furnace. The product directly leaving the boiler then is a CO_2-rich stream that is ready for sequestration or use with only modest conditioning. Conditioning is required to dry the CO_2, remove oxygen to prevent corrosion in the pipeline, and possibly other contaminants and diluents such as nitrogen, SO_2 and NOx.

The U.S. Department of Energy is investigating the feasibility of retrofitting boilers using this concept as a strategy for CO_2 recovery from conventional pulverized coal plants. This approach was conceived nearly twenty years ago at Argonne National Laboratory (ANL) as a low-cost CO_2 source for enhanced oil recovery (EOR). A molar ratio of CO_2/O_2 of about 3 is necessary to preserve the heat transfer performance and gas path temperatures, allowing this system to be applied as a retrofit. ANL is studying all the engineering aspects of this system, including the effect of impurities, such as SO_2 and NOx, and CO_2 transportation, use, and options for long-term sequestration. If the flue gas can be recycled before SO_2 scrubbing, significant cost savings are possible.

This project will provide the power industry with a low-cost retrofit system that could remain in service during future upgrades at the power plant. The captured CO_2 can be used for EOR or sequestered. Overall, this project addresses both design and full energy-cycle issues pertaining to our current coal-fired power plants.

Primary Project Goal

The goal of the project is to conduct comparative engineering assessments of technologies for the recovery, transportation, and utilization/disposal of CO_2 produced in high-efficiency, coal-based, energy systems. Coordinated evaluations will address CO_2 transportation, CO_2 use, and options for long-term sequestration. Commercially available CO_2 capture technologies will provide performance and economic baselines for comparing innovative CO_2 recovery technologies across the full energy-cycle.

Objectives

- The major objective is to develop engineering evaluations for the recovery of CO_2 from pulverized-coal-fired power plants retrofitted for flue-gas recirculation and to reconcile and extend these studies across the full energy-cycle.
- Another object is to extend this analysis to identify plants that may be retrofit candidates considering the effects of different coals and the accessibility of a sequestration zone.

CO_2 Capture for PC-Boiler Using Flue-Gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options

Accomplishments

An oxygen-blown KRW coal-gasification plant producing hydrogen, electricity, and supercritical CO_2 was studied in a full-energy cycle analysis extending from the coal mine to the final destination of the gaseous product streams to establish energy and cost comparisons against a Vision 21 facility.

A full energy-cycle was evaluated based on simulation of an O_2 blown PC boiler with CO_2 recovery and flue-gas recirculation that includes details of the stream compositions for the whole system.

A transport-reservoir injection simulation that can handle noncondensable and contaminate gases was validated.

A study that shows the cost-effectiveness for flue gas recirculation vs. monoethanolamine (MEA) scrubbing for CO_2 capture was completed.

It has been shown that CO_2 does not interfere with the scrubbing of SO_2 from a stream with a high concentration of CO_2.

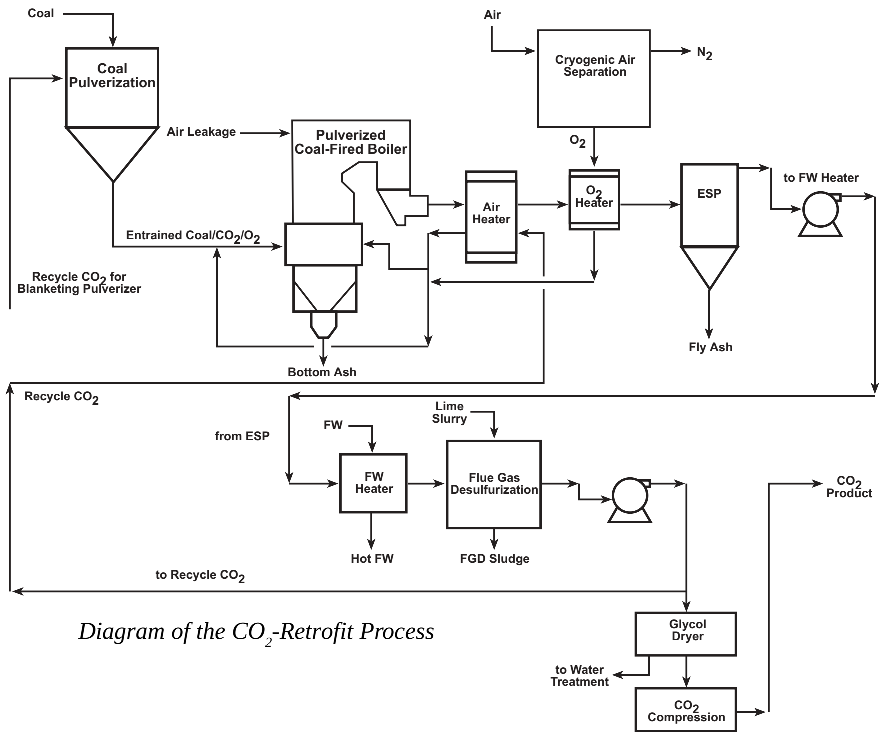
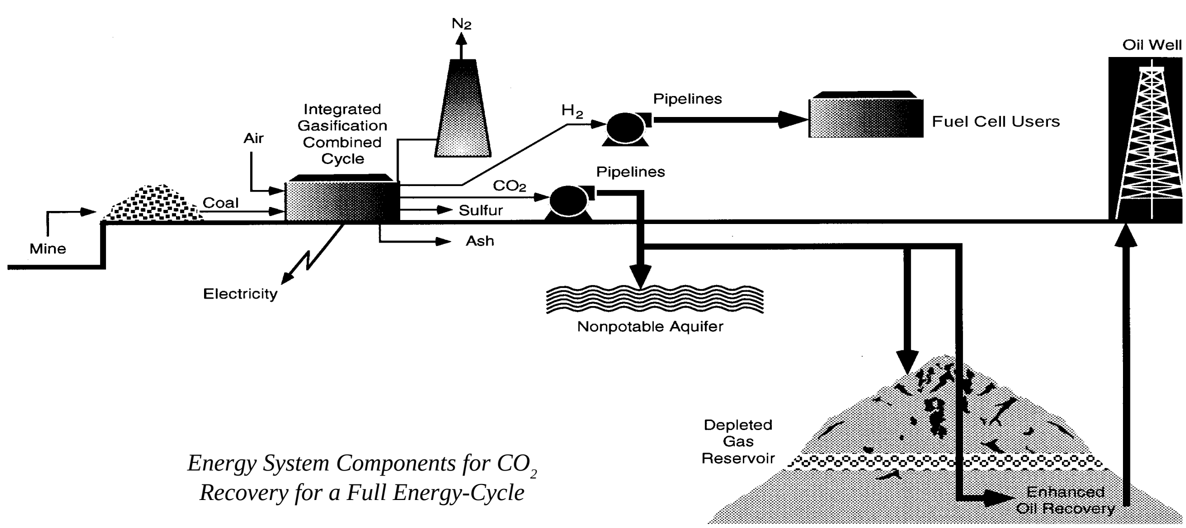


Diagram of the CO_2-Retrofit Process

Benefits

Pulverized coal plants are the most common type of power plant; therefore, a system that can be retrofit to such boilers and enable CO_2 recovery will have broad applicability. Flue gas recirculation eliminates the need for N_2/CO_2 separation and sulfur separation, permitting more economical CO_2 recovery than competing amine systems. Technical and economic analyses will build on current accomplishments to develop a lower cost CO_2 capture technology.



Energy System Components for CO_2 Recovery for a Full Energy-Cycle

Proj203.pmd

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

10/2002

GREENHOUSE GAS EMISSIONS CONTROL BY OXYGEN FIRING IN CIRCULATING FLUIDIZED BED BOILERS

PRIMARY PARTNER

Alstom Power Inc.
ABB Lummus Global, Inc.
Praxair, Inc.
Parsons Energy and Chemical Group

TOTAL ESTIMATED COST

Total	$1,996,486
DOE	$1,597,189
Non-DOE	$ 399,297

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Background

The object of oxygen-fired combustion is to burn the fuel in enriched air or pure oxygen to produce a concentrated stream of CO_2. Oxygen fired combustion presents significant challenges, but also provides a high potential for technology breakthroughs and a step-change reduction in CO_2 separation and capture costs. Barriers and issues include: 1) oxygen from cryogenic air separation is expensive, and oxygen combustion consumes several times more oxygen than gasification; 2) combustion of fuels in pure oxygen occurs at temperatures too high for existing boiler or turbine materials, while CO_2 recycle to control temperature increases the parasitic power load.

Development and costing of an optimized oxygen fired combustion scheme requires an engineering study to identify and resolve the technical issues related to application of oxygen firing with flue gas recycle to a boiler and its associated process heaters. Alstom Power has proposed a two-case approach in which evaluations would analyze both fossil fuel (coal and petroleum coke) based and biomass based circulating fluidized bed (CFB) for power production. The first case will be to identify and analyze normal baseline conditions for CFB combustion with air firing, both without CO_2 capture and with a novel high-temperature CO_2 capture and sorbent regeneration process. Then, CFB-based concepts, employing an oxygen/flue gas mixture as the oxidizing agent, will be studied to determine what operating conditions and gas clean-up processes are most economical. The CO_2 concentration in the flue gas can be greatly increased by using oxygen instead of air for combustion.

In the second case, indirect combustion of coal, also known as chemical looping, will be evaluated. In chemical looping, synthesis gas (a mixture of CO and H_2) reduces a solid transition metal oxide to a lower oxidation state in a fluidized bed reactor with the production of water and CO_2. The off gas stream is cooled to condense water and produce a pure CO_2 stream for sequestration. The reduced metal containing solid is transferred to a second fluidized bed reactor, where it is reoxidized with air. This exothermic reaction heats the oxygen-depleted air, which is sent to power production.

Comparisons will be made with the Integrated Gasification Combined Cycle (IGCC) cases that have already been evaluated by Parsons Energy and Chemical Group. In this way, important features that can improve plant operations by utilizing oxygen firing will be explored, identified, and included in plant designs.

GREENHOUSE GAS EMISSIONS CONTROL BY OXYGEN FIRING IN CIRCULATING FLUIDIZED BED BOILERS

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Primary Project Goal

The overall project goal is to conduct economic evaluations of the recovery of carbon dioxide using a newly constructed CFB combustor while burning coal, petroleum coke, or biomass fuel with a mixture of oxygen and recycled flue gas, instead of air.

Objectives

- The Phase I objective is to determine which of the new concepts in a CFB are technically feasible and have the potential of reducing the target cost of carbon avoided.
- Petroleum coke and coal samples will be combustion tested in a 4-inch Fluid Bed Combustion reactor to determine their gaseous (NO_x, SO_2, CO) and unburned carbon emissions and ash agglomeration/sintering potentials during combustion in oxygen-rich environments.
- The Phase II objective is to generate a refined technical and economic evaluation of the most promising concept for reducing CO_2 mitigation costs (based on recommendations from Phase I), based on data from proof-of-concept testing of the most promising concept.

Accomplishments

The performance analysis of the base case (Air-Fired) CFB has been completed. Key results included plant-efficiency, equipment costs, cost of electricity, and CO_2 mitigation costs. Work has been initiated on design/performance analyses of:

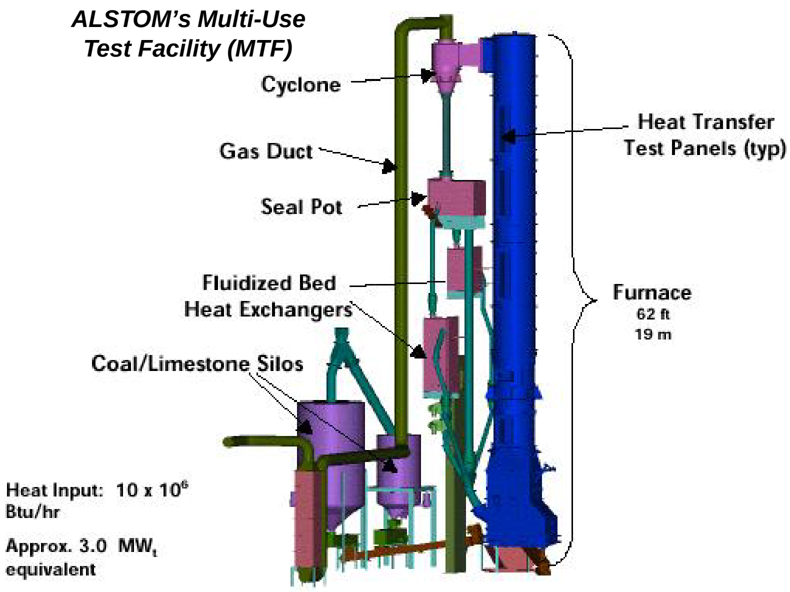
- Three advanced O_2-fired CFB concepts
- One high temperature carbonate regeneration process
- One chemical looping concept
- Two IGCC cases (one base case without CO_2 capture and one with a water-gas shift reactor to capture CO_2).

Coal and petroleum coke samples have been acquired, analyzed, and prepared; the modification of the 4-inch FBC is underway.

Benefits

The results from this project will provide the power industry with concrete data concerning greenhouse gas emissions control by oxygen firing in circulating fluidized bed boilers. The comparison of the several different technologies will target the most economical gas clean-up configuration.

ALSTOM's Multi-Use Test Facility (MTF)



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*Factsheet Under Development

Carbon Dioxide Capture by Absorption with Potassium Carbonate*
-University of Texas at Austin

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*Factsheet Under Development

An Integrated Modeling Framework for Carbon Management Technologies*
-Carnegie Mellon University

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*Factsheet Under Development

Zero Emissions Power Plants Using SOFCs and Oxygen Transport Membranes*
-Siemens Westinghouse Power Corp. - Pittsburgh

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***Factsheet Under Development**

Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO2*
-Princeton University

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U.S. Department of Energy
National Energy Technology Laboratory

08/2002

Sorbent Development for Carbon Dioxide Separation and Removal — Pressure Swing Adsorption & Temperature Swing Adsorption

Background

Selective separation of CO_2 can be achieved by the preferential adsorption of the gas on high-surface area solids. Conventional physical adsorption systems are operated in pressure swing adsorption (PSA) and temperature swing adsorption (TSA) modes. In PSA, the gas is absorbed at a higher pressure. Then pressure is reduced to desorb the gas. In TSA, the gas is absorbed at a lower temperature. Then, the temperature is raised to desorb the gas. PSA and TSA are some of the potential techniques that could be applicable for removal of CO_2 from high-pressure gas streams, such as those encountered in Integrated Gasification Combined Cycles (IGCC).

Primary Project Goal

The object of this project is to develop regenerable sorbents that have high selectivity, high regenerability, and high adsorption capacity for CO_2 — properties critical for the success of the PSA/TSA process.

Objectives

- Develop a new class of more efficient sorbents that are operational at moderate or high temperatures.
- Complete a system analysis with moderate/high temperature PSA/TSA processes for separation of CO_2, along with molecular simulations of CO_2/surface interactions.

PRIMARY PARTNER

National Energy Technology Laboratory

Carnegie Mellon University

Süd Chemie

DOE FUNDING PROFILE

Prior FY's	$ 400,000
FY2002	$ 400,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$ 800,000

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Sorbent Development for Carbon Dioxide Separation and Removal — Pressure Swing Adsorption & Temperature Swing Adsorption

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Accomplishments

Several zeolites from Süd Chemie were tested and have shown promising results.

Multi-cycle reactor tests showed that the highest adsorption capacity was observed when the major cation of the zeolites was sodium. A new class of sorbents (not zeolites) was prepared at NETL with excellent regenerability and high CO_2 adsorption capacity. Carnegie Mellon University (CMU) has initiated molecular simulations of CO_2 adsorption on zeolites in order to understand the selective adsorption process in zeolites. CMU is also conducting process simulation work on CO_2 Pressure Swing Adsorption to determine the optimal process. This process simulator, once validated, will be useful in developing sorption process performance estimates.

NETL developed sorbent

Benefits

The project shows considerable promise for developing a more energy efficient PSA process. This could also be applicable for removal of CO_2 from high-pressure gas streams, such as those encountered in Integrated Gasification Combined Cycle (IGCC) systems.

Proj190.pmd

*Factsheet Under Development

CO_2 Scrubbing with Regenerable Sorbent*
-NETL

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***Factsheet Under Development**

Novel Amine-Enriched Sorbents*
-NETL

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*Factsheet Under Development

NO_2 & NOx and CO_2 Removal with Aqua Ammonia*
-NETL

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*Factsheet Under Development

Modular CO_2 Capture Facility*
-NETL

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Sequestration

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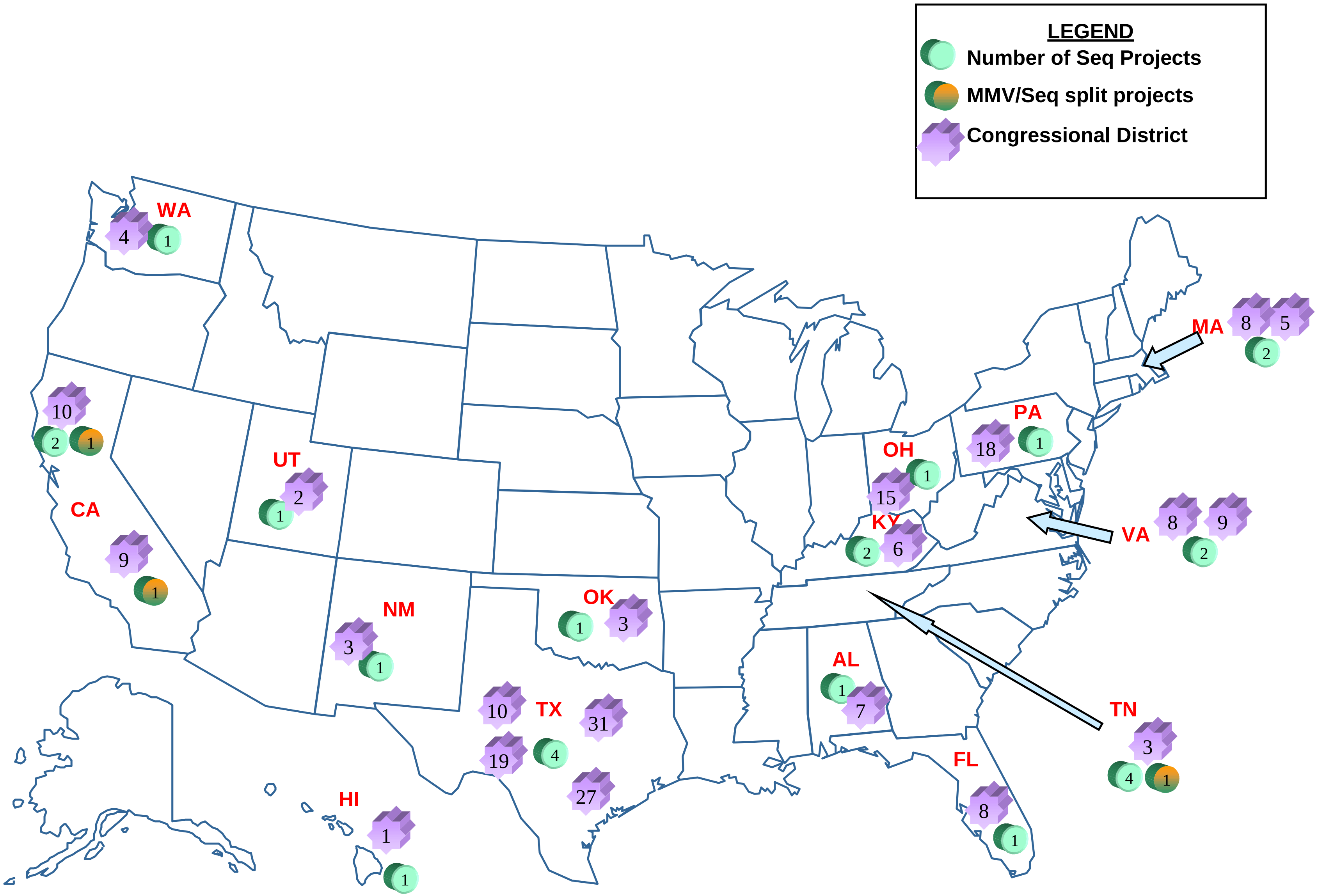
S-1



Doesn't include NETL Projects

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Project Title	Primary Contractor	Congressional District
Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide	Oklahoma State University/Penn State University	OK03
Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama	Alabama Geologic Survey	AL07
Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers	University of Texas at Austin (BEG)	TX10
Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide	Texas Tech University	TX19
Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds	Advanced Resources International/ BP Amoco	VA08
Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams	Consol	PA18
Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production	University of Kentucky Research Foundation	KY06
CO_2 Sequestration Potential of Texas Low-Rank Coals	Texas Engineering Experiment Station	TX31
Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau	University of Utah	UT02
Experimental Evaluation of Chemical Sequestration of CO_2 in Deep Saline Formations	Batelle Columbus Laboratories	OH15
GEO-SEQ	LBNL	CA09
GEO-SEQ	LLNL	CA10
GEO-SEQ	ORNL	TN03
Effects of Temperature and Gas Mixing in Underground Coalbeds	Oak Ridge National Laboratory	TN03
Feasibility of Large-Scale CO_2 Ocean Sequestration	Monterey Bay Aquarium Research Institute	CA10
Environmental Permitting	PICHTR	HI01
Ocean Carbon Sequestration (Offshore hydrate evaluation)	Naval Research Laboratory	FL08
International Collaboration on CO_2 Sequestration (CO_2 Ocean injection)	MIT	MA08
Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean	University of Massachusetts	MA05

Enhancement of Terrestrial C Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians	Stephen F. Austin State University	TX27
Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services	Virginia Polytechnic Institute and State University	VA09
Carbon Sequestration on Surface Mine Lands	University of Kentucky	KY06
Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil Fueled Electric Generation	Tennessee Valley Authority	TN03
Exploratory Measurements of Hydrate and Gas Compositions	LLNL	CA10
Enhanced Practical Photosynthesis Carbon Sequestration	ORNL	TN03
Soil Enhances from Solid Wastes	PNNL ORNL	WA04 TN03
Advanced Plant Growth (The plant-centric component)	LANL	NM03

(NETL projects not included)

Sequestration - *Geological*

Technology Target

$ Depleted Oil & NG Reservoirs - Feasibility of CO_2 storage and enhanced gas recovery
$ Deep Coal Seams - Field demos of max CO_2 storage in coal seams
$ Saline Aquifers - CO_2/fluid interactive studies
-Data base
-Field demos of aquifer storage

Deep coal seams
$ Lab tests for reservoir modeling studies
$ Effects on CO_2 on major coal types
$ Site selection criteria

Saline Aquifers
$ CO_2-fluid interactive studies
$ Geochemical and flow models

Depleted oil & NG reservoirs
$ Geochemical research
$ Database on cap rock
$ Modeling & testing for maximized storage of CO_2
$ Erosion of cement and corrosion of steel and possible cross effects

Other Studies
$ Modeling & Assessment
$ Indoor bioreactor
$ Shale

Consol ($7M)(01-08)
$ Sequestration of CO_2 in coal seams.
$ Economics.
$ CO_2 injection into degassed unmineable coal seam.
ARI ($1.8M)(00-04)
$ Geologic sequestration of CO_2 in unmineable coal beds.
$ Demonstrate N_2/CO_2 - ECBM and CO_2 seq. process.
$ Develop matrix and simulation.
Alabama Geo Survey ($0.79M)(00-03)
$ Geologic screening criteria.
$ Potential of specific site, mapping, target areas and capacity.
Oklahoma State Univ./PSU ($0.82M)(98-03)
$ Adsorption behavior of gas mixtures of CO_2 in CBM.
ORNL ($0.5M)(02-03)
$ Effects of temperature and gas mixing in underground coal beds.
Texas Engr.Exp ($0.36M)(02-04)
$ Evaluate the feasibility, environmental and economic impacts of seq. CO2 in Texas low-rank coal bed
NETL ($0.315M)(02-03)
$ Geology and reservoir simulations for coal seam sequestration
NETL ($0.37M)(02-03)
$ Physics and chemistry of coal seam sequestration and coal bed methane production

Project Funding: DOE $12M / Shared $7.3M

Battelle Columbus Labs ($3.2M)(02-04)
$ Conduct reservoir simulation in regional aquifer.
Univ. of Texas ($3M)(02-04)
$ Development of expertise in design and performance assessment of CO_2 disposal facilities.
Texas Tech Univ. ($2M)(00-03)
$ Characterize 3-phase flow in aquifers
$ Establish physical property correlations of CO_2, H_2O & limestone.
University of Utah ($0.3M)(00-03)
$ Multiphase behavior of CO_2 in saline aquifers.
NETL ($0.36M) ($0.79M) ($0.13M) (02-03)
1. Geology and reservoir simulation for brine field
2. Investigation of gas/water/rock interaction and chemistry
3. Activation of carbonation minerals for CO_2 Seq

Project Funding: DOE $9.79M / Shared $2.4M

BP Carbon Capture Project

Texas Tech Univ. ($0.11M)(02-03)
$ Capability of depleted gas reservoirs for CO_2 storage.
$ PVT relationship with CO_2 mix & gas reservoir.
$ Develop guidelines for selecting optimal CO_2 reservoir candidates.
SINTEF ($0.055M)(02-03)
$ Estimate the risk of CO_2 leakage and cross-effect (steel and concrete) from abandoned Petroleum wells.
Utah State Univ. ($0.043M)(02-03)
$ Reservoir simulation.
$ Reservoir characterization.
$ Fault leakage.

Project Funding: DOE $0.21M / Shared $0.21M

GEO-SEQ (LLNL, LBNL, ORNL) ($2.3M*)(00-05)
$ Joint project between academia and industry.
$ Optimize models with economic benefits.
$ Improve capacity assessment.
$ Field demonstration program.

Project Funding: DOE $2.3M / Shared $5.9M

*GEO-SEQ split 50/50 with MMV

Univ. of Kentucky ($0.36M)(02-05)
$ Investigate shale's ability to release CH_4 by CO_2 adsorption.

ORNL ($.17M)(99-02)
$ Practical photosynthesis conversion

NETL ($0.52M)(02-03)
$ Geologic sequestration core flow lab

Project Funding: DOE $1.4M / Shared $0.17M

NETL

Sequestration - *Terrestrial & Ocean*

Technology Target:

$ Assess domestic opportunities in mined-land reclamation
$ Complete field testing in representative regional terrestrial ecosystems
$ Demonstrate the multiple benefits associated with terrestrial sequestration
$ Identify and assess potential perturbations from ocean sequestration process
$ Assurance of predictability of CO_2 fate in oceans sequestration

Terrestrial Outcomes
$ Demonstrate the reforestation of surface mine lands with high value hardwoods
$ Afforestation and reforestation/ enhancement activities for tradable credits

Ocean Outcomes
$ Pathway viability and long-term sequestration stability
$ Flow models
$ Feasibility study of CO_2 storage as a hydrate pool in bottom of the ocean

Stephen F. Austin ($0.63M)(00-03)
$ Enhancement of terrestrial sinks by optimizing silvicultural techniques
$ Model the reforestation of abandoned mine lands in the Appalachian region for carbon sequestration and forest products

Virginia Tech ($0.49M)(02-05)
$ Restoring sustainable forests on Appalachian mined lands for wood products, renewable energy, carbon sequestration, and other ecosystem services

University of Kentucky ($1.0M)(02-05)
$ Carbon sequestration on surface mine lands
$ Study both the effects of tree species and spoil type and handling on carbon sequestration

ORNL/ PNNL ($1.4M)(00-04)
$ Investigate the use of industrial byproducts as soil enhancers

LANL ($1.76M)(00-04)
$ Advanced plant growth

TVA ($0.73M)(00-03)
$ Carbon capture by planting vegetation on existing coal-mined land

Project Funding: DOE $6.0M / Shared $1.2M

MBARI ($0.813M)(00-02)
$ Investigate the chemical, physical, and biological behavior of CO_2 hydrates in the deep ocean

LLNL ($0.86M)(98-2004)
$ Synthesize well-characterized CO_2 hydrates for testing

PICHTR ($0.062M)(2002)
$ Environmental permitting

NRL ($0.576M)(99-03)
$ Offshore hydrate evaluation
$ Conducted a detailed site survey of the Kona test site

MIT ($0.95M)(98-02)
$ Develop instrumentation and potential experiments for the International project on CO_2 ocean sequestration

University of Mass. ($0.206M)(02-04)
$ Establish a data base for the improvement of deep water ocean sequestration using a CO_2-H_2O limestone emulsion

NETL ($0.5M)(2002)
$ Hydrate formation, water tunnel flow properties, and deep-ocean injection study

Project Funding: DOE $3.9M / Shared $0.35M

Sequestration Project Fact Sheet List

Project Title	Primary Contractor	Fact Sheet Listing
Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide	Oklahoma State University/Penn State University	S-8
Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama	Alabama Geologic Survey	S-10
Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers	University of Texas at Austin (BEG)	S-12
Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide*	Texas Tech University	S-14
Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds	Advanced Resources International/ BP Amoco	S-16
Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams*	Consol	S-18
Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production*	University of Kentucky Research Foundation	S-20
CO_2 Sequestration Potential of Texas Low-Rank Coals*	Texas Engineering Experiment Station	S-22
Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau*	University of Utah	S-24
Experimental Evaluation of Chemical Sequestration of CO_2 in Deep Saline Formations	Batelle Columbus Laboratories	S-26
Geological Sequestration of CO_2 : GEO-SEQ*	LBNL, LLNL, ORNL	S-28
Effects of Temperature and Gas Mixing in Underground Coalbeds*	Oak Ridge National Laboratory	S-30
Feasibility of Large-Scale CO_2 Ocean Sequestration*	Monterey Bay Aquarium Research Institute	S-32
Environmental Permitting*	PICHTR	S-34
Ocean Carbon Sequestration (Offshore hydrate evaluation)*	Naval Research Laboratory	S-36
International Collaboration on CO_2 Sequestration (CO_2 Ocean injection)*	MIT	S-38
Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean*	University of Massachusetts	S-40
Enhancement of Terrestrial C Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians	Stephen F. Austin State University	S-42
Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services*	Virginia Polytechnic Institute and State University	S-44

* Factsheet Under Development

(BP and UCR projects not included)

* Factsheet Under Development

PROJECT facts

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

11/2002

UNMINABLE COALBEDS & ENHANCING METHANE PRODUCTION SEQUESTERING CARBON DIOXIDE

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Background

One method for sequestering carbon dioxide (CO_2) is to store it in natural geological formations, such as unminable coal seems. Most of the gas present in coal seams is stored on the internal surfaces of the organic matter. Because of its large internal surface area, coal can store 6 to 7 times more gas than the equivalent volume of a conventional gas reservoir. Most coal seams contain methane, the gas content generally increases with coal rank, depth of the coalbed, and reservoir pressure. Unmineable coalbeds are attractive targets for sequestration of CO_2 because they have a large storage capacity and the sequestered CO_2 can enhance the recovery of natural gas by displacing the methane that is present in the coalbeds.

Oklahoma State University is leading an effort to investigate and test the ability of injected carbon dioxide to enhance coalbed methane production. The specific focus of this project is to investigate the competitive adsorption behavior of methane, CO_2, and nitrogen on a variety of coals. Measurements are focused on the adsorption of the pure gases, as well as mixtures. Data will be taken on coals of various physical properties at appropriate temperatures, pressures, and gas compositions to identify the coals and conditions for which the proposed sequestration applications are most attractive.

Mathematical models are being developed to describe accurately the observed adsorption behavior. The combined experimental and modeling results will be generalized to provide a sound basis for performing reservoir simulation studies. These studies will evaluate the potential for injecting CO_2 or flue gas into coalbeds to simultaneously sequester CO_2 and enhance coalbed methane production. Future computer simulations will assess the technical and economic feasibility of the proposed process for specific candidate injection sites.

Primary Project Goal

The overall goal of this project is to develop accurate prediction methods (models) for describing the adsorption behavior of gas mixtures on coal over a complete range of temperature, pressure, and coal types.

Accomplishments

Several types of coals were characterized by their ability to adsorb nitrogen, methane, and CO_2. The low pressure adsorption of CO_2 and methane was studied in a volumetric apparatus. Significant progress in improving the predictive capability of the models has been made. The research will eventually determine how much methane is displaced by a given amount of CO_2.

Unminable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide

PROJECT PARTNERS

Oklahoma State University

Penn State University

Geo-Environmental Engineering
State College, PA

COST

Total Project Value	\$674,980
DOE	\$624,078
Non-DOE Share	\$ 56,125

Objectives

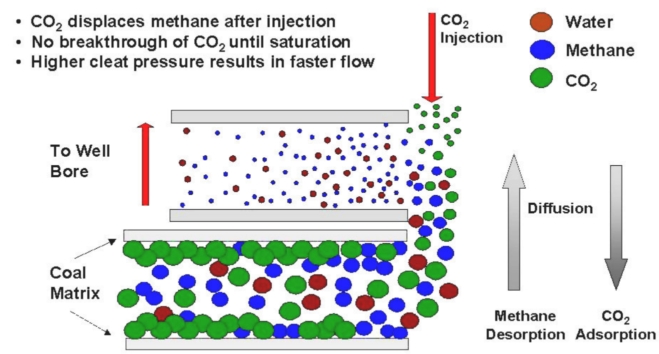
Proposed fourth year milestones

- Measure pure methane adsorption on three different coals and dry activated carbon.
- Develop and validate reliable, simple, analytic models capable of describing multi-layer adsorption.
- Further evaluate the vapor/liquid equilibrium analog model for possible prime candidate for use in CBM and CO_2 sequestering simulators.
- Study the adsorption of binary and ternary gas mixtures.

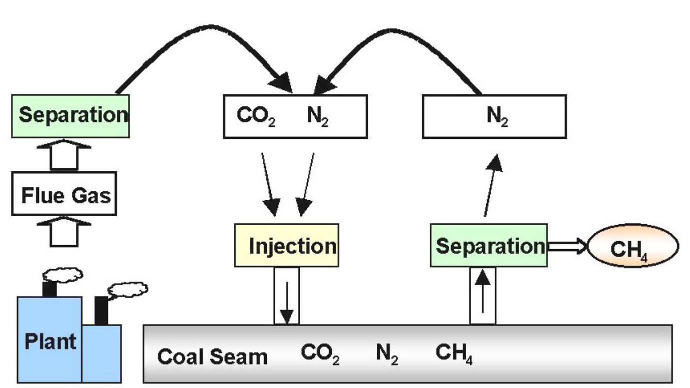
Benefits

This project will significantly enhance our understanding of multilayer adsorption of near critical and supercritical components on heterogeneous surfaces. The data and models developed will permit evaluation of the ability of coal to sequester CO_2, a major greenhouse gas, and simultaneously increase the supply of methane, a clean-burning energy source, and provide a sound basis for commercial implementation of this technology.

Physical Depiction of CO_2-Enhanced Methane Recovery



Concept of Capture and Injection of CO_2 and/or N_2



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GEOLOGIC SCREENING CRITERIA FOR SEQUESTRATION OF CO_2 IN COAL: QUANTIFYING POTENTIAL OF THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

Background

The amount of carbon dioxide (CO_2) in the Earth's atmosphere has risen substantially since the start of the industrial age. This increase is attributed widely to the burning of fossil fuels, and if current trends in resource utilization continue, anthropogenic CO_2 emissions will triple during the 21st century. Among the principal ways CO_2 emissions from power plants can be addressed is to sequester this greenhouse gas in geologic formations. Within the geologic formations that can potentially store CO_2 are unminable coalbeds. Coalbeds are an especially attractive target because coal can store large quantities of gas. In this process of being adsorbed, the CO_2 displaces adsorbed methane. Thus, the sequestered CO_2 serves as a sweep gas to enhance recovery of coalbed methane.

The coalbed methane fairway of the Black Warrior basin is a logical location to develop screening criteria and procedures from numerous standpoints. According to the U.S. Environmental Protection Agency, Alabama ranks 9th nationally in CO_2 emission from power plants and two coal-fired power plants are within the coalbed methane fairway. More than 34 billion cubic meters of coalbed methane have been produced from the Black Warrior basin, which ranks second globally in coalbed methane production. Production is now leveling off, and enhanced coalbed methane recovery has the potential to offset impending decline and extend the life and geographic extent of the fairway far beyond current projections.

The Geological Survey of Alabama and its partners are conducting research to determine the amount of CO_2 that can be stored in the Black Warrior coal-bed methane region of Alabama.

Primary Project Goal

The primary goal of this project is to develop a screening model that is widely applicable, quantify CO_2 sequestration potential in Black Warrior CBM fairway, and apply screening modeling to identify favorable demonstration sites for CO_2 sequestration.

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Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane Fairway, Alabama

PROJECT PARTNERS

Geological Survey of Alabama
Tuscaloosa, Alabama

University of Alabama

Alabama Power Company
Bringingham, Alabama

Jim Walter Resources
Brookwood, Alabama

COST

Total Project Value:	$1,398,068
DOE	$ 789,565
Non-DOE Share:	$ 608,503

Objectives

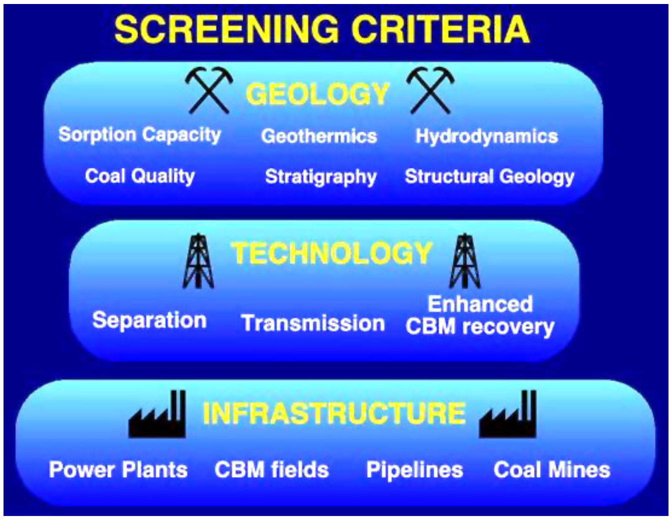
- Develop a geologic screening model for CO_2 sequestration sites that is widely applicable.
- Quantify the CO_2 sequestration potential of coals in the Black Warrior coalbed methane fairway, where two coal-fired power plants operate adjacent to a thriving coalbed methane industry.
- Apply the screening model to identify sites favorable for demonstration of enhanced coalbed methane recovery and mass sequestration of CO_2 emitted from coal-fired power plants in this basin of Alabama.

Accomplishments

Subsurface geological analyses have been performed on the Pottsville formation from the Black Warrior coalbed methane fairway. Hydrologic and geothermic data have been collected from more than 2,800 well logs and are being used to calculate reservoir pressure and geothermal gradient. Preliminary results confirm that coal can sorb significantly more carbon dioxide than methane while having relatively little capacity for nitrogen.

Benefits

The developed screening model will provide a widely applicable tool for evaluating potential geological sites for sequestration of CO_2. Ultimately, this project will result in sequestration of CO_2 and enhanced methane recovery from unmineable coalbeds. The technology results of the project will be transferred to the public, academia, and industry for application toward ultimate commercialization of sequestration technologies.



Variables that will be used to develop the screening model.

Proj211.pmd

PROJECT facts

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

11/2002

OPTIMAL GEOLOGICAL ENVIRONMENTS FOR CARBON DIOXIDE DISPOSAL IN SALINE AQUIFERS

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Background

For CO_2 sequestration to be a successful component of the U.S. emissions reduction strategy, there will have to be a favorable intersection of a number of factors, such as the electricity market, fuel source, power plant design and operation, a suitable geologic sequestration site, and a pipeline right-of-way from the plant to the injection site. The concept of CO_2 sequestration in saline water-bearing formations (saline reservoirs), isolated at depths below potable aquifers, became of widespread interest in the early 1990's and is in the process of maturing from a general concept to one of the options used by oil and gas producers for isolating excess produced CO_2.

The University of Texas at Austin's Bureau of Economic Geology is developing criteria for characterizing optimal conditions and characteristics of saline aquifers that can be used for long-term storage of CO_2. Phase I of this project included identifying drilling locations for CO_2 injection wells and better defining saline-formation conditions suitable for CO_2 disposal and sequestration. During Phase II, saline water-bearing formations outside of oil and gas fields were investigated.

Recent research and development efforts have demonstrated the technical feasibility of the process, defined costs, and modeled technology needed to sequester CO_2 in saline aquifers. One of the simplifying assumptions used in previous modeling efforts is the effect of stratigraphic complexity on transport and trapping in saline aquifers. Phase III efforts will include field testing of a limited amount of CO_2 injected into a deep saline reservoir within the state of Texas to ascertain the interaction of the gas with the reservoir rock and to monitor the size and shape of the CO_2 plume within the reservoir.

Primary Project Goal

This project will develop and then apply criteria for characterizing saline aquifers for long term sequestration of CO_2. Current effort is directed at a field test of injecting a set amount of CO_2 into a deep saline reservoir and monitoring the interaction of the gas with the reservoir and the dispersion of the CO_2 with time.

Objectives

- Provide an appropriate target site for development of expertise in design and performance assessment of CO_2 disposal facilities.

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers

PROJECT PARTNERS

University of Texas at Austin

Texas American Resources

B-P America

Schlumberger

Bureau of Economic Geology

Austin Texas

Lawrence Berkeley National Laboratory

Lawrence Livermore National Laboratory

Oak Ridge National Laboratory

COST

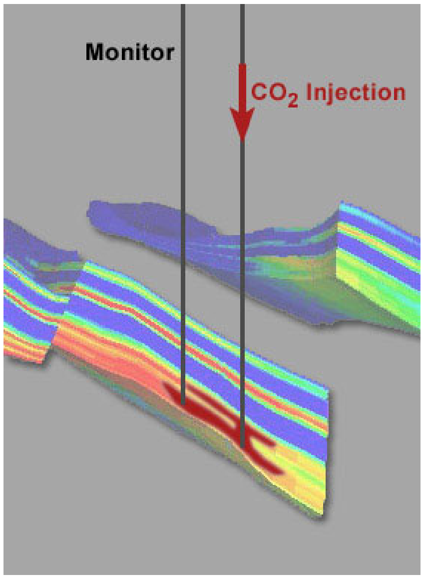
Total Project Value:	$3,659,215
DOE	$2,909,215
Non-DOE Share:	$ 750,000

- Adequately characterize the field site for CO_2 disposal in a saline reservoir.
- Monitor behavior and migration of the CO_2.
- Develop conceptual models for CO_2 behavior.
- Provide information needed to characterize conditions affecting long-term containment of CO_2.

Accomplishments

Phase I of the project plotted the distribution and 1996 CO_2 output of power plants in the U.S. Geologic screening criteria for identifying suitable saline water-bearing formations for CO_2 sequestration were developed. Sufficient data was obtained about the properties of saline water-bearing formations in the pilot test areas to develop a prototype Geologic Information System (GIS) to demonstrate the effectiveness of this approach. The pilot study confirmed that information is available, either as basin-specific data sets or as products of geologic analogs and play analysis. Efforts were focused on reservoir and geological play analyses and geologic and hydrologic models to extrapolate from areas with abundant data into water-bearing formations with little data to identify those saline water-bearing formations that have the geological attributes conducive to successful pilot sequestration projects.

Phase II involved a regional inventory of geological environments of saline water-bearing formations for CO_2 disposal. This effort was focused on reservoir and geological play analyses and geologic and hydrologic models to extrapolate from areas of abundant data into poorly known water-bearing formations and identified those parts of saline water-bearing formations that have the geological attributes conducive to ensuring success of pilot sequestration projects. Phase III effort will highlight through field test, the degree to which CO_2 can be injected in saline aquifers.



Conceptual model of sequestering CO_2 in saline aquifers.

Benefits

This project will benefit industry by extending modeling and monitoring capabilities for sequestration into the geologic settings where very large-scale sequestration is feasible in the geographic areas where sequestration is needed. Non-productive brine bearing formations below and hydrologically separated from potable water have been widely recognized as having high potential for very long term (geologic time scale) sequestration of greenhouse gasses, and this site will provide a first field scale testing in this setting. It will also provide a regional U.S. data inventory of saline water-bearing formations.

Proj210.pmd

*Factsheet Under Development

Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide*
-Texas Tech University

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PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Sequestration

03/2003

Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

Background

One approach to sequestering carbon dioxide (CO_2) is to inject it into deep, unminable coal seams. A particular advantage of coalseam sequestration is that coal seams can store several times more CO_2 than the equivalent volume of a conventional gas reservoir because coal has a large surface area. Another advantage of coalseams is that not only does such a process sequester CO_2, but methane is displaced which can be recovered and sold to help offset costs. This process is known as enhanced coalbed methane recovery, or ECBM. Advanced Resources International and their partners are using the only long-term, multi-well ECBM projects that exist in the world today to evaluate the viability of storing CO_2 in deep, unminable coal seams. The two existing ECBM pilots are located in the San Juan Basin in northwest New Mexico and southwestern Colorado. The knowledge gained from studying these projects is being used to verify and validate gas storage mechanisms in coal reservoirs, and to develop a screening model to assess CO_2 sequestration potential in other promising coal basins of the U.S.

The two field pilots, the Allison Unit (operated by Burlington Resources) and the Tiffany Unit (operated by BP America) are demonstrating CO_2 and nitrogen (N_2) ECBM recovery technology respectively. The interest in understanding how N_2 affects the process has important implications for power plant flue gas injection, since N_2 is the primary constituent of flue gas. Currently, the cost of separating CO_2 from flue gas is very high. This project is evaluating an alternative to separation by sequestering the entire flue gas stream. Another reason for considering CO_2/N_2 is that N_2 is also an effective methane displacer, improving methane recoveries and further decreasing the net cost of CO_2 sequestration. The Allison Unit pilot area, which has been in operation since 1995, includes 16 producer wells and 4 injector wells. The Tiffany Unit pilot area, which has been in operation since 1998, in made up of 34 producer wells and 12 injector wells. This demonstration project is providing valuable new information to improve the understanding of formation behavior with CO_2 injection, the ability to predict results and optimize the process through reservoir modeling.

Primary Project Goal

The primary goal of this project is to develop a technical understanding of the CO_2-sequestration/ECBM process by studying the two field projects, integrating this knowledge with laboratory tests, and transferring that new knowledge to industry by developing an easy-to-use screening model that can quickly assess the feasibility of CO_2 sequestration at any given site based on coal seam data and injected gas properties.

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GEOLOGIC SEQUESTRATION OF CO_2 IN DEEP, UNMINEABLE COALBEDS: AN INTEGRATED RESEARCH AND COMMERCIAL-SCALE FIELD DEMONSTRATION PROJECT

PARTNERS AND PERFORMERS

Advanced Resources International, Inc.

Burlington Resources

BP America

TOTAL ESTIMATED COST

Total Project Value	$5,543,246
DOE	$1,387,224
Non-DOE Share	$4,156,022

Objectives

Location of the Tiffany and Allison Units

- Demonstrate N_2/CO_2 ECBM recovery and CO_2 sequestration in deep, unminable coalbeds.
- Develop a software model that can be used by industry to screen site-specific sequestration opportunities in coalbeds.
- Document field procedures.
- Perform a scoping assessment of the potential for CO_2 sequestration in deep, unmineable coal seams across the U.S.
- Perform supporting research in sorption behavior in various coal types and develop performance studies into multi-component coal sorption behavior, the potential for matrix swelling of the coal with CO_2 injection, and the potential for geochemical reactions between coal moisture and CO_2 that could adversely affect injectivity.
- Transfer results to a broad industrial base.

Accomplishments

The field studies have clearly demonstrated that ECBM via CO_2/N_2 injection and CO_2 sequestration in coal seams is technically feasible. Field and laboratory data has provided important new insights on the process, such as the tendency for coal to "swell" when it comes into contact with CO_2, reducing injectivity. New light has also been shed on the processes of methane displacement by CO_2. These findings will have important implications for designing and implementing future CO_2-sequestration/ECBM projects, and are being incorporated into the project screening model. An national assessment has indicated that this approach has the potential to sequester 90 billion tonnes of CO_2, and provide an additional 150 trillion cubic feet of gas supply for the U.S.

Benefits

The knowledge gained from this project will benefit the electric power generation industry by providing verifiable and valid CO_2 storage mechanisms in coal reservoirs, as well as a new source of clean gas supply. The ability to take advantage of these opportunities will be facilitated by the development of a screening model to assess CO_2 sequestration and ECBM potential.

CO_2 Injector Well at the Allison Unit

Proj228.pmd

*Factsheet Under Development

Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams*
-Consol

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*Factsheet Under Development

Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production*
-University of Kentucky Research Foundation

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*Factsheet Under Development

CO_2 Sequestration Potential of Texas Low-Rank Coals*
-Texas Engineering Experiment Station

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*Factsheet Under Development

Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau*
-University of Utah

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PROJECT facts

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

03/2003

STORAGE OF CO_2 IN THE GEOLOGIC FORMATIONS IN THE OHIO RIVER VALLEY REGION

Background

Storage of carbon dioxide (CO_2) in a dense, supercritical phase in deep saline sandstone formations is deemed to be a very promising long-term option for sequestration. Deep saline formations are among the largest and most widely available potential reservoirs for long-term storage. Usable formations are known to exist underneath much of the continental U.S. and under the oceans. In both locations, these formations appear to have abundant disposal capacity. Moreover, many of these formations are often located in close proximity to major point sources of CO_2 emissions such as fossil-fuel power plants, which has the benefit of reducing transportation costs of CO_2 to the injection site.

During the 1990s, Battelle researchers were some of the first scientists to be supported by the U.S. Department of Energy's National Energy Technology Laboratory to explore the potential of using deep geologic formations as a means of sequestering CO_2. The current project is in Phase III of Battelle's research; the first two Phases were funded under the "Global Climate Change - Novel Concepts for Management of Greenhouse Gases" program. Commencement of this effort underscores the progression of DOE's geologic sequestration program from computer and laboratory assessment towards pilot-scale testing and verification. Phase III is focused on a site characterization (surface and subsurface) for possible injection of CO_2 into a suitable formation.

In this project, the research team is planning a field study to determine whether the deep rock layers in the Ohio River Valley are suitable for storing carbon dioxide. The research team includes American Electric Power (AEP), which owns and operates the Mountaineer plant (the host site for the research project); Battelle, a non-profit organization, headquartered in Columbus Ohio, and is a global leader in technology development; the U.S. Department of Energy; BP; Schlumberger, and Pacific Northwest National Laboratory. The Ohio Coal Development Office of the Ohio Department of Development (OCDO) is also providing support to the project, given the potential to address future carbon emissions from the many coal-based electricity power plants in Ohio and to retain the jobs that these plants and Ohio coal mines support. Additional technical support is being provided by researchers from the West Virginia University, the Ohio Geological Survey, and several technology vendors. If the studies show that storing carbon dioxide deep underground in the Ohio River Valley will be safe, practicable, and effective, AEP and its partners will decide whether to go to the next stage.

Primary Project Goal

The project will involve site assessment to develop the baseline information necessary to make decisions about a potential CO_2 geologic disposal field test and verification experiment at the site. This project will be focused in the Ohio River Valley, which is home to the largest concentration of fossil-fuel fired electricity generation in the nation. Additionally, the potential for long-term sequestration of CO_2 in deep, regional sandstone formations and the integrity of overlying caprock will be evaluated for future sequestration projects. No CO_2 injection is planned during this phase.

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PARTNERS AND PERFORMERS

Battelle Memorial Institute

American Electric Power

Pacific Northwest National Laboratory

BP

Ohio Coal Development Office of the Ohio Department of Development

Schlumberger

Ohio Geological Survey

West Virginia University

TOTAL ESTIMATED COST

Total Project Value	$4,172,441
DOE	$3,151,441
Non-DOE Share	$1,021,000

STORAGE OF CO_2 IN THE GEOLOGIC FORMATIONS IN THE OHIO RIVER VALLEY REGION

Objectives

- Thoroughly assess the geologic environment in the Ohio River Valley in order to site a field test.
- Conduct a 2-dimensional seismic survey to delineate subsurface geologic structures.
- Drill an exploratory deep well to collect scientific data to assess the potential for conducting a CO_2 storage test at the site.
- Conduct tests to comprehensively characterize the reservoirs, caprocks, and overlying layers, thereby developing a thorough understanding of the geology, hydrogeology, and geochemistry at the site.
- Prepare the necessary permits and regulatory documents to allow use of the deep well to inject CO_2 captured from a nearby coal-fired power plant.
- Develop and apply a comprehensive Risk Analysis and Stakeholder Involvement Process for the capture, transport, injection, and long-term storage of CO_2 at the field demonstration site.
- Develop a comprehensive monitoring plan to ensure the safe, long-term isolation of CO_2 in deep geologic formations.

Prior Accomplishments

Prior research by Battelle scientists leading up to the current project includes:

- Regional data compilation, reservoir and geochemical simulations, geochemical experiments, and seismic aspects reports have been completed.
- A detailed report on engineering and economic aspects for CO_2 capture and storage has been completed.
- Regional-scale assessments in the Midwest and other regions show that there is enormous potential sequestration capacity in sedimentary basins with favorable formation thickness, hydrogeology, seismicity, and proximity to CO_2 sources. However, site-specific tests and characterization are needed to determined injection potential at individual locations.

Benefits


The Mountaineer Power Plant

Evaluating the feasibility of CO_2 storage at several different scales will allow the energy industry to prove the viability of an evolving U.S. technology that will allow fossil-fuel fired power plants to continue operating well into the future as our nation develops a strategy to deal with the buildup of greenhouse gases in the atmosphere. The project approach will allow the U.S. to more rapidly move the concept of carbon capture and geologic disposal from the laboratory to an industrial-scale demonstration. If the research shows that storage is feasible, it could offer a way for many utilities around the country to significantly reduce their carbon emissions. It will be especially beneficial to states such as West Virginia, Ohio, and many of the large industrial States in the Midwest, which depend heavily on coal for electricity generation. Finally, all aspects of the current project including field characterization, testing, permitting, and monitoring plans development will provide a protocol for similar investigations at other locations in the future.

Proj227.pmd

*Factsheet Under Development

Geological Sequestration of CO_2 : GEO-SEQ*
-LBNL, LLNL, ORNL

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*Factsheet Under Development

Effects of Temperature and Gas Mixing in Underground Coalbeds*
-Oak Ridge National Laboratory

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*Factsheet Under Development

Feasibility of Large-Scale CO_2 Ocean Sequestration*
-Monterey Bay Aquarium Research Institute

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***Factsheet Under Development**

Environmental Permitting*
-PICHTR

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*Factsheet Under Development

Ocean Carbon Sequestration (Offshore hydrate evaluation)*
-Naval Research Laboratory

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*Factsheet Under Development

International Collaboration on CO_2 Sequestration (CO_2 Ocean injection)*
-MIT

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*Factsheet Under Development

Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean*
-University of Massachusetts

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PROJECT **facts**

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

04/2003

ENHANCEMENT OF TERRESTRIAL CARBON SINKS THROUGH RECLAMATION OF ABANDONED MINE LANDS IN THE APPALACHIANS

Background

The continuing demand for fossil-fuel-based power and the associated rise in atmospheric carbon dioxide (CO_2) concentration will require the development of innovative ways to capture and store carbon. Terrestrial ecosystems, including both soil and the related vegetation, are recognized as significant biological CO_2 "scrubbers" and are major sinks for removing CO_2 from the atmosphere. Since reclaimed mined lands are essentially devoid of soil carbon, these areas provide an excellent opportunity to sequester carbon in both soils and vegetation.

Much of the strip mining in the Eastern U.S. is on forested lands. Unfortunately, after mining, most of these areas are restored as grasslands. However, much more carbon is stored in a hectare of forest than in a hectare of grasslands. Stephen F. Austin State University (SFASU) is studying the CO_2 sequestration potential resulting from afforestation of abandoned mined lands using Northern red oak. Within the Appalachian coal region, there may be up to 400,000 hectares of abandoned mined lands. These areas contain little or no vegetation, provide little wildlife habitat, and may pollute streams. Reclamation and afforestation of these sites has the potential to sequester large quantities of carbon in terrestrial ecosystems. Utility companies with high CO_2 emissions are interested in mitigating these emissions through the use of carbon credits. In order to establish a carbon credit market and claim carbon credits, utility companies need to partner with landowners who do not currently have forests on their land. Abandoned mined lands in Appalachia should offer excellent sites for such partnerships.

Primary Project Goal

The overall goal of this project is to sequester carbon in abandoned mine lands. This project will determine how to increase carbon sequestration in forests while increasing forest yields and providing other desirable ecosystem benefits.

Objectives

- To determine the profitability of forest management in the Appalachian region when only timber is considered and when both timber and carbon credits are considered.
- To determine optimal forest management schedules using Forest Management Optimizer (FORMOP).
- To determine the amount of carbon that can be sequestered on abandoned mined lands.

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Enhancement of Terrestrial Carbon Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians

PARTNERS

Stephen F. Austin State University

Texas Utilities Electric Company

USDA Forest Service

TOTAL ESTIMATED COST

Total Project Value	$839,504
DOE	$628,169
Non-DOE Share	$211,335

Accomplishments

FORMOP, a combination of the U.S.D.A. Forest Service's growth and yield models and dynamic and economic programs, was used to simulate tree growth as a function of variables such as site quality, thinning frequency and intensity, and rotation length. Results indicate that costs of sequestering carbon in Northern red oak stands on West Virginia abandoned mined lands range from $7.20-40.50/tonne. These numbers reflect the cost of carbon sequestration without considering profits from timber management. When the timber revenues are taken into consideration, the net revenue earned from the reforestation of these lands ranges from a profit of approximately $34/tonne of carbon to a loss of $40/tonne. The market price of carbon credits will determine the attractiveness of sequestration projects on these poorer quality mined lands.

Benefits

Mine reclamation, afforestation and forest management can provide two major benefits. The first is financial. Growing forests can generate revenue, create jobs, and enhance local economies. The second is environmental. Afforestation can reduce the negative effects of global warming by storing carbon in trees, enhance wildlife habitat, improve air and water quality, reduce soil erosion, and increase recreational opportunities.

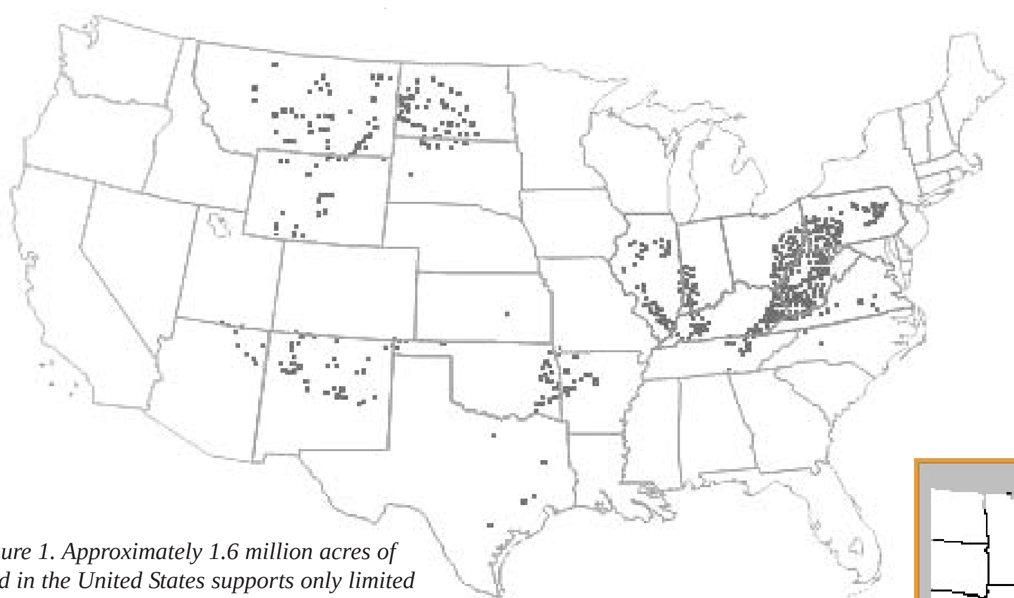

Figure 1. Approximately 1.6 million acres of land in the United States supports only limited vegetation due to past and present mining operations.

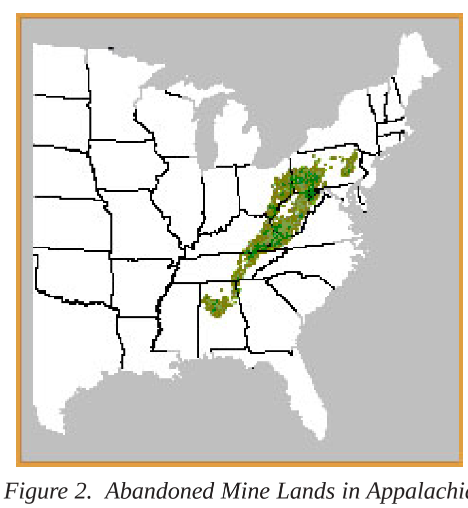

Figure 2. Abandoned Mine Lands in Appalachia

*Factsheet Under Development

Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services*
-Virginia Polytechnic Institute and State University

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*Factsheet Under Development

Carbon Sequestration on Surface Mine Lands*
-University of Kentucky

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PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

10/2002

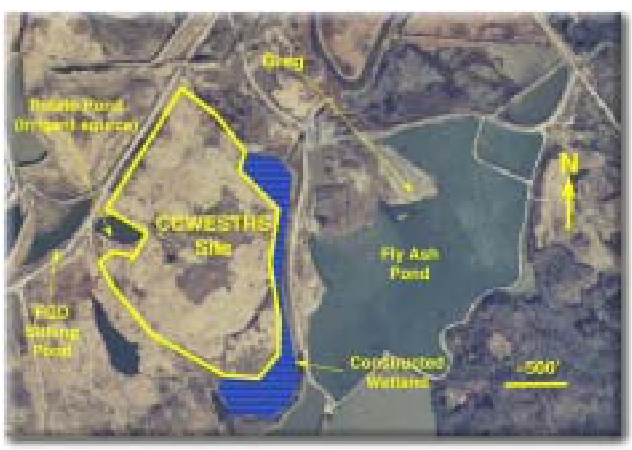
CARBON CAPTURE AND WATER EMISSIONS TREATMENT SYSTEM (CCWESTRS) AT FOSSIL-FUELED ELECTRIC GENERATING PLANTS

Background

A 100-acre reclaimed surface mine area at the 2,558-megawatt Tennessee Valley Authority (TVA)-owned Paradise Fossil Plant near Drakesboro, Kentucky, is serving as the demonstration site where by-products from the plant's wet scrubber will be used to amend the soils. Wastewater from the flue gas desulfurization process that targets SO_2 control and selective catalytic reduction for NO_X control will be used to irrigate the trees and herbaceous cover. The plants will in turn capture and store carbon dioxide while reducing pollutant loadings to the local watershed.

The "Carbon Capture and Water Emissions Treatment System" (CCWESTRS) will be constructed at the Paradise Fossil Plant on existing, poorly reclaimed coal mined land by establishing plantings of vegetative species. Sequestration will occur through carbon uptake by trees, with biomass recovery for the forest products industry, and in the soil, which currently has low carbon levels. An average of 1.5 to 3 tons of carbon per acre/year is estimated to be sequestered in the CCWESTRS over a 20-year period.

The Tennessee Valley Authority will design and install a system to drip irrigate Flue Gas Desulfurization (FGD) wastewater over the entire site. Tree growth and response, along with other relevant observations will be performed over the course of the project through 2003 to determine effectiveness of the integrated technologies to sequester carbon and accomplish other project benefits.



PRIMARY PROJECT PARTNERS

National Energy Technology Laboratory

Tennessee Valley Authority

Electric Power Research Institute

CUSTOMER SERVICE

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WEBSITE

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Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil-Fueled Electric Generating Plants

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The FGD water poses the major obstacle for the project. Toxic in most respects and requiring treatment before its ultimate discharge into the Green River, the FGD water contains certain boron compounds, which hinder growth and survival of trees and other plants at concentrations above 2-4 mg/l. The Paradise FGD water has over ten times that concentration.

Flue Gas Desulfurization wastewater pond

Primary Project Goal

To demonstrate a "whole plant" approach using by-products from a coal-fired power plant to sequester carbon in an easily quantifiable and verifiable form.

Objectives

- Provide economically competitive and environmentally safe options to off-set projected growth in U.S. baseline emissions of greenhouse gases after 2010
- Achieve the long-term goal of $10/ton of avoided net costs for carbon sequestration
- Provide half of the required reductions in global greenhouse gases by 2025

Benefits

- Developing a potentially widely applicable passive technology for water treatment for criteria pollutant release reductions
- Using power plant by-products to improve coal mine land reclamation and carbon sequestration
- Developing wildlife habitat and green-space
- Generating Total Maximum Daily Load (TMDL) credits for water and air-borne nitrogen
- Developing additional forest lands that will be available for timber harvesting

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*Factsheet Under Development

Exploratory Measurements of Hydrate and Gas Compositions*
-LLNL

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***Factsheet Under Development**

Enhanced Practical Photosynthesis Carbon Sequestration*
-ORNL

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*Factsheet Under Development

Soil Enhances from Solid Wastes*
-PNNL/ORNL

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*Factsheet Under Development

Advanced Plant Growth (The plant-centric component)*
-LANL

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AN INVESTIGATION OF GAS/WATER/ROCK INTERACTIONS & CHEMISTRY

- Develop reservoir or basin scale models that include flow, mass transport, and chemical reaction processes for CO_2 injection and field pilot test sites.

Accomplishments

The facilities to conduct hydrothermal CO_2-water-rock reactions and analyze these complex mixtures have been developed at NETL. Work on the systematic study of the solubility of CO_2 in increasingly complex salt solutions is currently underway.

In addition to construction of a database containing physical and chemical information on over 64,000 brine wells, NETL has added information on the locations of coal-fired power plants and information on seismic activity. A composite map depicting the power plants, saline formations, and seismic potential was constructed. The high-pressure chemistry of CO_2 with brines sampled around the nation has been started. The pertinent reactions have been identified and the effect of temperature, pressure, pH, and other variables determined. Lastly, several simulations of brine field sequestration have been developed. These include development of sophisticated reservoir models as well as reactive transport models.

Benefits

This project will provide useful information in the area of reaction kinetics dealing with carbon dioxide and surrounding minerals and also provide a compiled brine database of some 64,000 brine wells in the United States. By compiling a database of these brines along with power plants and seismic activity in the United States, a more efficient means of storage can take place in optimal locations. Taking nearby power plant emissions and local seismic activity into consideration, researchers and engineers become more informed as to where precautions need to be taken or simply where areas of higher risk are located. Thus, an understanding of the fundamental chemistry associated with the reactions coupled with a detailed brine database provides much needed information and efficiency to the actual sequestration projects. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that may further increase global warming.

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AN INVESTIGATION OF GAS/WATER/ROCK INTERACTIONS & CHEMISTRY

Background

About two thirds of the United States is underlaid by deep saline aquifers that have an estimated CO_2 adsorption capacity of between 320 to 10,000 billion tons. Unfortunately, there are a large number of uncertainties associated with the heterogeneous reactions which may occur between CO_2, the brine, and minerals in the surrounding strata—especially with respect to reaction kinetics. This project focuses on the complex solution and surface chemistry of CO_2 in brines in the presence of host rock and the special types of analyses required to study the reaction kinetics. Carbonate mineral formation/dissolution reactions that may be important in geologic sequestration in deep saline aquifers will be identified. The kinetics of CO_2 dissolution in the liquid phase and subsequent substrate-water reactions are slow and poorly understood. Understanding the kinetics of both these types of reactions and the processes controlling them is essential to understanding the conversion of CO_2 into stable carbonate minerals.

A compilation of existing brine data from a variety of sources, and a complete statistical analysis of the brine chemistry and other geological parameters associated with brine aquifers would be a valuable tool for both experimental and modeling studies of CO_2 sequestration in brines. Currently, NETL is developing a brine database that includes temperature, depth, pressure, and a variety of chemical variables (pH, sodium, iron, chloride, bicarbonate, calcium, magnesium, sulfate, and total dissolved solids) on some 64,000 brines taken from the contiguous United States. Sources of these data include those provided by the USGS, searches of geoscience literature, State Geological Surveys and oil and gas producing companies. Additionally, NETL has instituted a limited field program of brine collection throughout the United States. This brine sampling is being done in conjunction with other government agencies and oil and gas companies.

Primary Project Goal

The ultimate objective of the work being performed jointly at NETL and the United States Geological Survey is to carry out an experimental study to assess the role of the chemistry of formation water in CO_2 solubility. Then the role of rock mineralogy in determining the potential for CO_2 sequestration through geochemical reactions will be assessed.

Objectives

- Investigate kinetics of CO_2 dissolution in brines at temperatures and pressures appropriate for deep saline aquifer carbon dioxide sequestration.
- Improve the understanding of the processes by which mineral carbonates are formed and study the reactivity of various mineral substrates involved in these processes.
- Assess and collect both brines and surrounding geologic strata in selected brine formations in the conterminous United States in order to determine their potential to sequester CO_2 from fossil fuel fired power plants.

PRIMARY PARTNERS

National Energy Technology Laboratory
United States Geological Survey
Parsons Power
Battelle Memorial Institute
University of Pittsburgh
California University of Pennsylvania
University of Texas
Case Western Reserve University

DOE FUNDING PROFILE

Prior FY's	$682,000
FY2002	$817,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$1,499,000

CUSTOMER SERVICE

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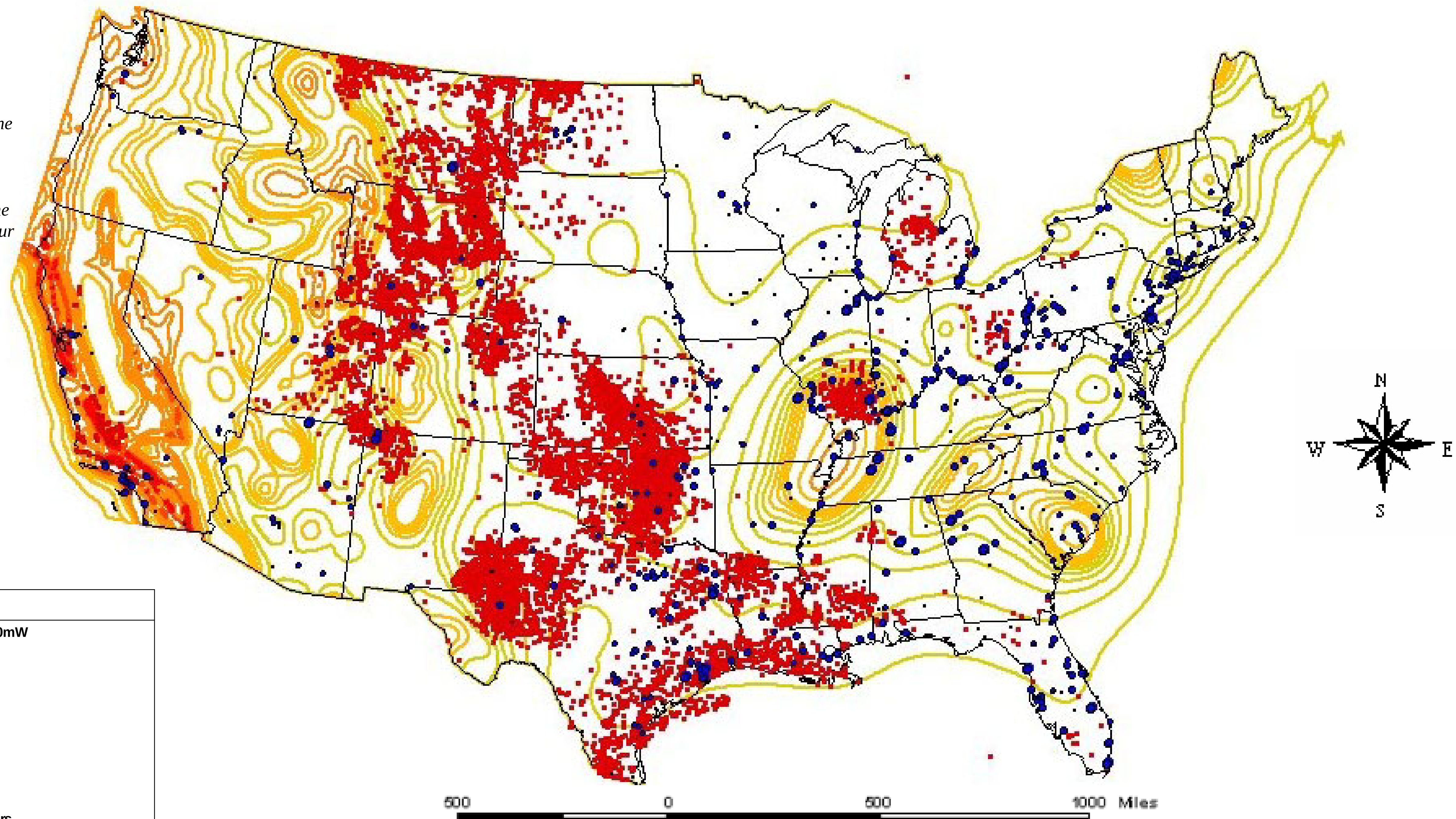
GEOLOGIC SEQUESTRATION OF CARBON DIOXIDE
Powerplant Locations • Brine Well Locations • Seismic Potential

The black circles on the map indicate the location of the fossil fuel fired power plants. The size of the black circles is proportional to the megawattage of the power plant. The gray areas indicate the location of brine wells, while the contour lines indicate seismic potential.



LEGEND

Power Plants Nameplate Capacity >= 100mW
- 100 - 420 MW
- 421 - 875 MW
- 876 - 1469 MW
- 1470 - 2242 MW
- 2243 - 3969 MW

US States
US Counties
Brine Wells

Peak Ground Acceleration,
10% Probability of Exceedance in 50 years

0 - 6 ft/sec/sec	Albers Equal Area Projection
7 - 15 ft/sec/sec	Clarke 1866 Spheriod
16 - 40 ft/sec/sec	Central Meridian -96.0
41 - 60 ft/sec/sec	Reference Latitude 37.5
61 - 100 ft/sec/sec	2nd Standard Parallel 45.5

Power generation data derived from EPA Emissions and Generation Resource Database 1996 (E-GRID96) and DOE/EIA 767.
Geological coverages derived from data set generated under DOE/NETL contract by the University of Texas, Bureau of Economic Geology.

**** DRAFT by Garret Veloski DRAFT ****

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

08/2002

PHYSICS AND CHEMISTRY OF COAL-SEAM CO_2 SEQUESTRATION & COALBED METHANE PRODUCTION

Background

Recently, the concept and practice of carbon management via the sequestration of carbon dioxide by coal seams and the concurrent production of coalbed methane (CBM) have increased in potential significance. The injection of CO_2 into deep, unmineable, gassy coal seams may substantially increase CH_4 (methane) production above the level achievable by standard depressurization methods. Water continues to play a key role in CBM production, yet explanations in the coal literature of how water does this on a molecular scale are presently undeveloped. Thus, a fundamental understanding of the mechanism(s) by which sorbed water influences, or can influence, coalbed methane production, with and without CO_2 sequestration is necessary.

Additionally, research is being conducted to obtain information useful for assessing the technical feasibility of CO_2 sequestration in coal-seams. Areas of interest include estimation of the capacity of a coal-seam to adsorb CO_2 (*adsorption isotherm*), the validity of inter-lab comparisons of isotherm data (*inter-lab precision*), and the stability of the CO_2 saturated phase once formed—especially with respect to how it might be affected by changes in the post-sequestration environment (*environmental effects*). The affects of temperature, pressure, and coal rank on the ability of coal to adsorb CO_2 have been investigated.

Primary Project Goal

The goals of the research are to ultimately provide guidelines for drilling of new CBM production wells and enable field engineers to determine if cases of poor CO_2 sequestration and/or low methane productivity can be attributed to non-ideal coalbed temperatures/depths or, perhaps, to other factors.

Objectives

- Determine the temperature dependence of CO_2 sequestration and methane production.
- Determine adsorption isotherms for pure gases in a static system for coals of NETL interest.
- Develop a flow system to generate adsorption isotherms via numerical techniques established for data analysis.

PRIMARY PARTNERS

National Energy Technology Laboratory
Pennsylvania State University
University of Pittsburgh
University of Oklahoma
University of Southern Illinois
CSIRO
Netherlands Institute of Applied Geoscience TNO
Illinois State Geological Survey

DOE FUNDING PROFILE

Prior FY's	$257,000
FY2002	$441,207
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$698,207

CUSTOMER SERVICE

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NETL

Physics and Chemistry of Coal-Seam CO_2 Sequestration & Coalbed Methane Production

Accomplishments

Advanced CO_2/CH_4 Concepts (CO_2 sequestration & CBM production):
A method for simultaneously accounting for heats of CO_2 and CH_4 sorption/desorption, moles of CO_2 and CH_4 sorbed/desorbed, extents of dehydration, and sample temperature was developed and a manuscript was prepared and accepted for presentation at various conferences. Mathematical methods for resolving complex calorimetric thermograms were developed. Accordingly, an apparent correlation between hypothetical extents of coal dehydration and predicted relative viscosities of water in the narrow capillaries, mesopores, and micropores of coal was discovered.

CO_2 Sorption, Transport, & Environmental Chemistry (CO_2 Sequestration):
A static system for the measurement of adsorption isotherms was assembled, pressure-tested, and successfully employed to generate data along with a derived equation used to separate the actual surface adsorption from the effects of coal swelling on the isotherm shape. The extent of actual physical adsorption was determined, the heats of adsorption were calculated, and the values were found to agree within 10% of each other. NETL has developed a new theory that allows one to obtain information on coal swelling from the experimentally derived adsorption isotherm.

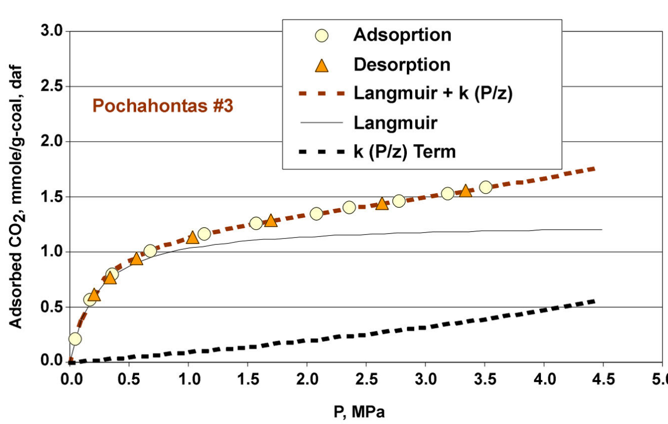
Benefits

This project will provide guidelines for both efficient sequestration of carbon dioxide in coal seams and enhanced methane production. Through an understanding of the fundamental chemistry involved in the CO_2 adsorption/CH_4 desorption process, it will be possible to select optimum conditions for CO_2-enhanced coalbed methane production/sequestration. The project has resulted in development of a new theory of coal swelling and how the CO_2 adsorption process affects swelling. The new theory allows one to obtain information on coal swelling from simple adsorption isotherm measurements. The enhanced methane production associated with CO_2 sequestration will help to defray sequestration costs. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that may further increase global warming.

NETL's New Theory on Coal Swelling

Adsorption Isotherms Appear to Be Combinations of a **Surface Adsorption Term** and a **Constant Term**

$$n_{\exp} = n_{ads} + k(P/z)$$



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Proj186.pmd

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

08/2002

OCEANIC SEQUESTRATION

Background

Stabilization of rising levels of atmospheric greenhouse, primarily CO_2, may require the use of non-atmospheric carbon sequestration options in addition to maximizing improvements in energy conversion, end-use efficiencies, and fuel switching to lower-carbon or carbon-free energy sources. One potential large-scale sequestration option is to directly inject CO_2 into the ocean at depths greater than 1500m where it should be effectively sequestered for hundreds of years or longer. Generally, the deeper the CO_2 can be deposited, the longer the residence time in the ocean.

The current effort is directed at determining the fate of CO_2 introduced into the deep ocean and how the icelike CO_2 hydrate impacts the process. The experimental work is carried out in two facilities: a High-Pressure, Variable-Volume View-Cell (HVVC) and a High-Pressure Water Tunnel Facility (HTWF). In addition, a Low-Pressure Water Tunnel Facility (LWTF) capable of being chilled has been constructed and used to test various configurations of flow conditioners and section divergence angle and length.

Primary Project Goal

The objectives of the research are to obtain information useful both for assessing the technical feasibility of oceanic CO_2 sequestration and for developing optimal methods of introducing the CO_2 into the ocean.

Objectives

- Determine hydrate formation and dissolution conditions as a function of dissolved CO_2 content, temperature, and pressure, especially at higher levels of dissolved CO_2.
- Characterize the flow patterns possible in the water tunnel test sections and develop predictive tools for designing the internal geometries necessary for optimum stability of CO_2 (or any fluid particle) over an anticipated range of simulated ocean depths.
- Initiate CO_2 drop injection experiments in the HWTF to investigate depth of injection and initial dissolved CO_2 content effects on the fate of CO_2.

PRIMARY PARTNERS

National Energy Technology Laboratory

University of Pittsburgh

DOE FUNDING PROFILE

Prior FY's	$ 0
FY2002	$ 475,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$ 475,000

CUSTOMER SERVICE

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WEBSITE

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NETL

Oceanic Sequestration

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Accomplishments

A theoretical model that predicts formation conditions for CO_2 and other hydrate-forming gases was developed during FY2001 along with an initial set of experiments used to validate this model. Results show that under conditions of temperature and pressure planned for deep-ocean sequestration, the formation of hydrate from dissolved CO_2 may be in areas of elevated dissolved CO_2 concentration, such as near the injection site.

High-Pressure Water Tunnel Facility in newly renovated laboratory

The flow conditioning elements were tested in the LWTF to determine the design parameters needed for stabilization of a CO_2 fluid particle in the HWTF over the range of anticipated ocean injection conditions. The precision of the measurements was improved and now the entire procedure can operate without intervention and automatically collects sets of profiles for different flow rates. Additionally, a full 3-D finite element analysis of the flow through the conditioner was initiated.

During FY2002, renovations to the Oceanic Sequestration Laboratory in Building 84, Rooms 119 and 125 were completed and the HWTF and supporting facilities were constructed. The HWTF is now operational and observations of CO_2 drops under simulated deep-ocean conditions can be seen.

Benefits

This project will provide useful information and models for the development and storage optimization of CO_2 in our oceans. By injecting carbon dioxide into the ocean at depths greater than 1500m, the risk of unnecessary human contact is removed and the carbon dioxide is placed as far from the atmosphere as possible. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that would further precipitate global warming.

CO_2 drop in the High-Pressure Water Tunnel at a simulated depth of 2000 m.

Proj189.pmd

*Factsheets Under Development

Geology and reservoirs simulation for coal seam sequestration*
-NETL

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*Factsheets Under Development

Geology and reservoirs simulation for brine field*
-NETL

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*Factsheets Under Development

Activation of carbonation minerals for CO_2 Sequestration*
-NETL

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*Factsheets Under Development

Geologic sequestration core flow lab*
-NETL

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Measurement Monitoring & Verification

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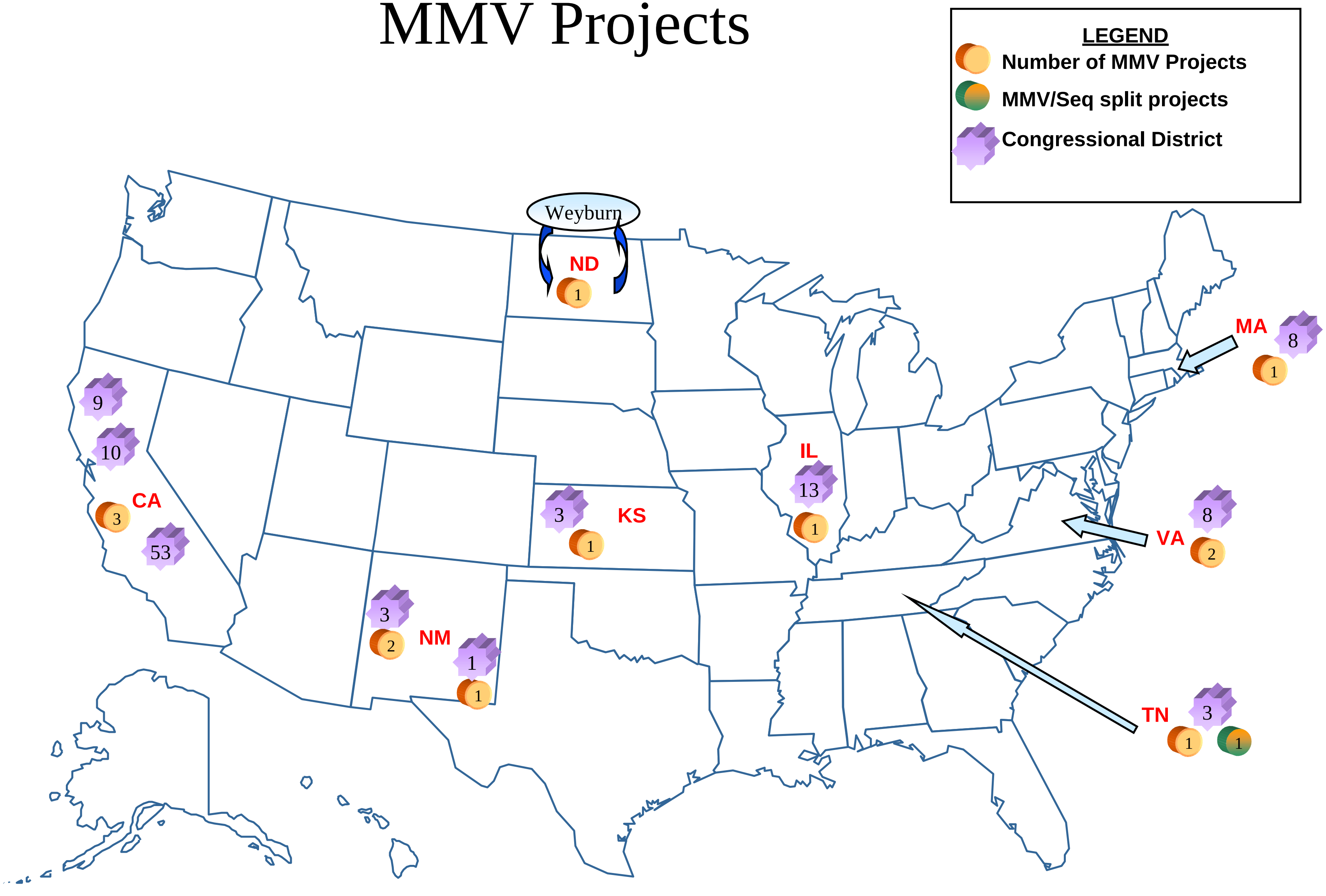
MMV Projects



*Includes BP. Doesn't include NETL

M-1

Measurement Monitoring & Verification Congressional Districts List

Project Title	Primary Contractor	Congressional District
Weyburn Carbon Dioxide Sequestration Project	Natural Resources Canada - CANMET	*Canada*
Natural Analogs for Geologic Sequestration	Advanced Resources International	VA08
A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration	University of California, San Diego	CA53
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	VA08
Development of a Carbon Management Geographic Information System for the US	MIT	MA08
Economic Evaluation of CO_2 Sequestration Technologies	Tennessee Valley Authority	TN03
MIDCARB (Interactive Digital Carbon Atlas)	University of Kansas Center for Research	KS03
CO2 Reservoir Improvements	ANL	IL13
Sequestration of CO_2 in a Depleted Oil Reservoir	Sandia National Laboratories	NM01
Sequestration of CO_2 in a Depleted Oil Reservoir	LANL	NM03
Ecosystem Dynamics and Econ. Anal	LANL	NM03
GEO SEQ Project (Project in Sequestration Area)	LBNL	CA09
GEO SEQ Project	LLNL	CA10
GEO SEQ Project	ORNL	TN03
Long Term CO_2 Monitoring, Containment, and Storage Technology Development (BP Project)	LLNL (BP)	CA10
Geologic Carbon Sequestration Monitoring and Modeling (BP Project)	LBNL (BP)	CA09

(NETL projects not included)

Measurement Monitoring and Verification

Technology Target

$ Indirect monitoring technology acceptable to permitting agency
$ Direct CO_2 monitoring
$ Reservoir monitoring test
$ Demonstrate advanced videography for accurate remote estimates of carbon inventories

- **Understanding of equilbria between multi component gases, oil, and water.**
- **Reliable monitoring and verification technology for CO_2 storage sites.**
- **Computer simulation model to effectively monitor CO_2 depleted oil reservoirs, abandoned coal mines, and saline aquifers.**
- **Remote sensing and non-intrusive measurement systems for carbon inventories**

Advanced Resources, Int. ($1.1M)(01-04)
$ Document empirically the capability of depleted oil and gas fields to sequester CO_2 safely and securely.

SNL(2.3M) **/ LANL**($1.1M) / (00-03)
$ Computer simulation model for field test including measurement of fluid pressure changes for depleted oil reservoirs

Natural Resources Canada ($3.4M)(02-03)
$ Weyburn Project
$ Develop monitoring techniques (surface Seismic & tracer injection)

TVA ($1.06M)(00-02)
$ Economic Evaluation of Sequest. Technologies

GEO-SEQ (2.3M*)(02-03)
$ LBNL - Seismic & EM imaging
$ LLNL - Electrical imaging
$ ORNL - Isotope tracers

LANL ($2.27M)(00-04)
$ Ecosystem dynamics and economic analysis

Nature Conservancy ($1.65M)(01-04)
$ Demonstrate and refine the tools and methodologies for cost-effective, verified measurements of the long-term potential of various carbon sequestration and land use emissions avoidance strategies.

Univ. of California - ($0.22M)(02-04)
$ Sleipner sea floor survey

NETL ($0.41M)
$ Comprehensive monitoring techniques to verify the integrity of geologic sequestered CO_2

NETL ($0.15M)
$ Direct monitoring of CO_2 surface leakage

Univ. of Kansas ($2.4M)(00-02)
$ Construct database to evaluate geological locations and characteristics of CO_2 sources.
$ Modeling & Assessment.

MIT ($0.825M)(02-05)
$ Development of a carbon management GIS for US

ANL ($0.56M)(02-03) {Task 5}
$ Application of automatic Differentiation (numerical method) for injected CO_2 in reservoir fluids.

Project Funding: DOE $17.4M / Shared $32M

BP Carbon Capture Project

Stanford University ($0.2M)(02-03)
$ Monitoring of injection of CO_2-Satellite Radar Inferrometry

LLNL ($0.15M)(02-04)
$ Monitoring of CO_2 storage sites
-Noble gas isotopes

LLNL ($0.15M)(02-04)
$ Geobotanical remote sensing for verifying CO_2 containment

LBNL ($0.09M)(2003)
$ Evaluate low-cost monitoring techniques (gravity, passive seismic, etc)

Tie-Line Technologies ($0.083M)(02-03)
$ Developing screening tool for minimum miscibility pressure for gas injection (effects of impurities in CO_2)

TNO-NITG ($0.017M)(2002)
$ CO_2 optimum monitoring methodology(2003)
$ Develop best practice manual

Project Funding: DOE $0.69M / Shared $0.69M

*GEO-SEQ split 50/50 with Sequestration (geologic)

Measurement Monitoring & Verification Project Fact Sheet List

Project Title	Primary Contractor	Fact Sheet Listing
Weyburn Carbon Dioxide Sequestration Project*	Natural Resources Canada - CANMET	M-5
Natural Analogs for Geologic Sequestration	Advanced Resources International	M-7
A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration*	University of California, San Diego	M-9
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	M-11
Development of a Carbon Management Geographic Information System for the US*	MIT	M-13
Economic Evaluation of CO_2 Sequestration Technologies*	Tennessee Valley Authority	M-15
MIDCARB (Interactive Digital Carbon Atlas)	University of Kansas Center for Research	M-17
CO_2 Reservoir Improvements*	ANL	M-19
Sequestration of CO_2 in a Depleted Oil Reservoir	Sandia National Laboratories / LANL	M-21
Ecosystem Dynamics and Econ. Anal*	LANL	M-23
GEO SEQ Project* (Project in Sequestration Area)	LBNL, LLNL, ORNL	Factsheet in Sequestration
Development of Comprehensive Monitoring Techniques to Verify the Integrity of Geologically Sequestered Carbon Dioxide	NETL	M-25
Development of Simulation Tools for Sequestration and Retention of CO_2 in Permeable Media*	NETL	M-27

(BP and UCR projects not included)

* Factsheet Under Development

*Factsheet Under Development

Weyburn Carbon Dioxide Sequestration Project*
-Natural Resources Canada - CANMET

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PROJECT facts

Sequestration

01/2003

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Natural Analogs for Geologic Sequestration

Background

Large geologic deposits of high-purity carbon dioxide (CO_2), created entirely by natural geologic processes, occur in many sedimentary basins. They have acted as relatively stable repositories for CO_2 over many thousands of years and prove that geologic sequestration offers a secure, environmentally sound way of storing CO_2. Most importantly, they provide an excellent natural laboratory in which to study the effects of long-term CO_2 exposure on the reservoir minerals. These conditions cannot be replicated by short term laboratory experiments or geologic sequestration tests. CO_2 fields may be viewed as unique "natural analogs" that can be used to assess crucial aspects of geologic sequestration. These assessments would include: integrity of storage, candidate site screening and selection, and operational safety and efficiency. Thus, these CO_2 deposits offer considerable potential for understanding and publicizing geologic sequestration and can serve to build public confidence in this CO_2 management technique.

At present, five large natural CO_2 fields in the United States provide a total of 25 million tons of carbon dioxide that is injected into oil fields for enhanced oil recovery (EOR). This project will perform a multi-disciplinary geologic engineering study of U.S. CO_2 deposits. The overall objective is to compare the naturally occurring CO_2 reservoirs with the capability of depleted oil and gas fields to securely and economically sequester carbon dioxide.

Primary Project Goal

The overall goal is to study natural CO_2 fields to document empirically, both to the scientific community and the public at large, the capability of depleted oil and gas fields to sequester carbon dioxide safely and securely. The effort will also investigate long-term reactions between CO_2 and the various minerals in the reservoir and cap rocks.

Objectives

- Evaluate the safety and security of geologic sequestration
- Adapt specialized CO_2 operations technology to an emerging sequestration industry
- Document analogs for public review

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CUSTOMER SERVICE

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WEBSITE

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Natural Analogs for Geologic Sequestration

PROJECT PARTNERS

Advanced Resources International

Kinder Morgan CO_2 Company, Ltd.

Ridgeway Petroleum Corporation

British Geological Survey NASCENT Project

Australian Petroleum Cooperative Research Center

TOTAL ESTIMATED COST

Total Project Value:	$1,736,390
DOE Share:	$1,123,390
Non-DOE Share:	$ 613,000

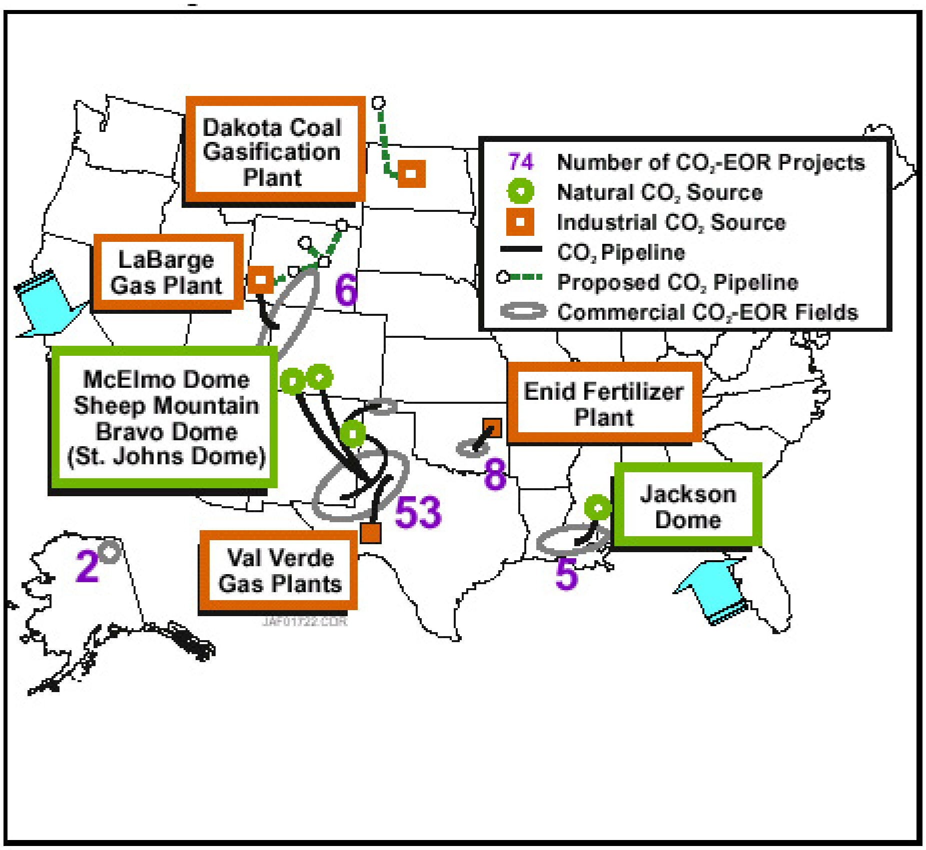
- Evaluation of environmental and safety related factors will be made based on the results of a geochemical analysis of CO_2 impacts and geochemical modeling

Accomplishments

Literature reviews and collection of geologic and reservoir data have been performed. ARI is about one-third of the way towards completing the first comprehensive analysis of three large natural CO_2 fields: Kinder Morgan's McElmo field in Colorado, Ridgeway's St. Johns Dome in Arizona and New Mexico, and Denbury Resources' Jackson Dome field in Mississippi. Existing well log and other geologic information has been collected and is currently being used to build robust geologic models of the three fields.

Benefits

This project will provide information that can be used to develop technologies for safe and secure sequestration of CO_2 in natural geologic formations. Furthermore, the project provides an opportunity to study CO_2 sequestration in a non-intrusive manner at natural sites and to obtain data not otherwise obtainable on the long-term effect of CO_2 on mineral strata.



Location of natural CO_2 study sites in the USA and the CO_2 infrastructure for EOR projects

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*Factsheets Under Development

A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration*
-University of California, San Diego

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PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Sequestration

04/2003

Application and Development of Appropriate Tools and Technologies for Cost-Effective Carbon Sequestration

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TOTAL ESTIMATED COST

Total Project Value	$2,065,425
DOE	$1,652,340
Non-DOE Share	$ 413,085

Background

According to the Intergovernmental Panel on Climate Change (IPCC), deforestation accounts for about 20 percent of annual global emissions of carbon dioxide (CO_2), the primary greenhouse gas (GHG). The IPCC estimates that 12 to 15% of the fossil fuel CO_2 emissions between 1995 and 2050 could be offset through slowing tropical deforestation, allowing these forests to regenerate, and engaging in plantation plantings and other forms of agroforestry.

There is great potential for such cost-effective carbon sequestration projects both in the United States and abroad. However, without the development and refinement of tools and technologies that allow accurate and cost-effective assessment of the amount of carbon sequestered, these approaches may not be recognized as a credible means for reducing GHG. Through the ongoing development and implementation of carbon sequestration projects on a demonstration scale, The Nature Conservancy is participating in a cooperative agreement with the Department of Energy to explore the compatibility of carbon sequestration in terrestrial ecosystems with the conservation of biodiversity. The Conservancy's first involvement in assessing this approach came in 1994 with the development of the Rio Bravo Carbon Sequestration Pilot Project in Belize, in cooperation with several partners. Since then, several other projects have been initiated with a variety of partners.

This project will focus on gaining cost-effective, verified measurements of the long-term potential of various terrestrial carbon sequestration strategies and assessing land use practices that avoid emissions of CO_2. The project will use newly developed aerial and satellite-based technology to study forestry projects in Brazil and Belize to determine their carbon sequestration potential and will also test new software models to predict how soil and vegetation store carbon at sites in the United States and abroad.

Primary Project Goal

The primary goal of this project is to refine the tools and methodologies for cost-effective, verified measurements of the long-term potential of various carbon sequestration strategies and assessing land use practices that avoid emissions of CO_2, using actual projects as proving grounds.

Application and Development of Appropriate Tools and Technologies for Cost-Effective Carbon Sequestration

PARTNERS

The Nature Conservancy (TNC)

Winrock International Institute for Agricultural Development

The Society for Wildlife Research (SPVS)

Programme for Belize

Comite de Defensa de la Fauna y Flora (CODEFF)

Universidad Austral de Chile

Los Alamos National Laboratory

Colorado State University

Stephen F. Austin State University

Virginia Technical University

ADDITIONAL SUPPORT

American Electric Power
General Motors
Texaco

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Objectives

- Improve carbon monitoring and lower its cost
- Develop land use trend models to project potential CO_2 offsets
- Evaluate and standardize carbon monitoring methods and procedures
- Assess domestic land-use options for reducing greenhouse gases
- Develop software for initial feasibility screening of potential domestic projects.

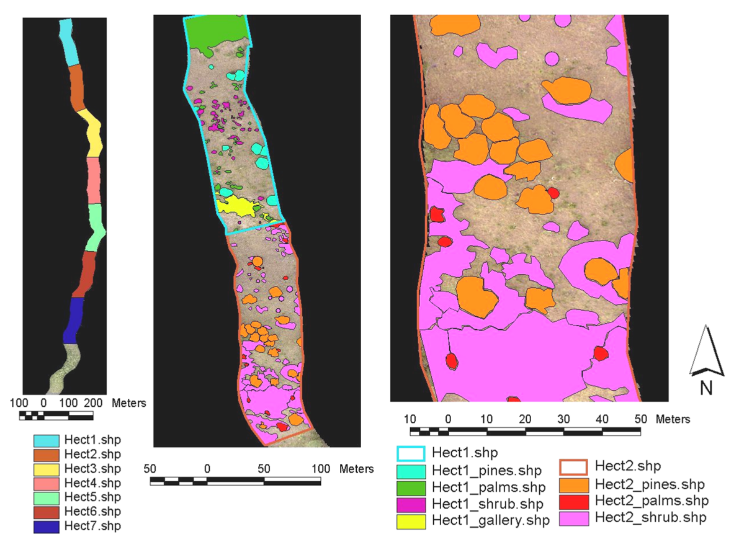
Accomplishments

Advanced videography has been applied for pine savannah analysis in Belize. Feasibility studies on several different U.S. ecosystems have been initiated to determine for which of these ecosystem types carbon sequestration is a viable option. The GEOMOD spatial analysis tool has been used to determine and validate baseline analyses. An alternative baseline method developed by TNC, called the Euclidean Distance between Agriculture and Forest (EDAF) method, has been further refined in baseline analyses in Brazil. A technical advisory panel was organized to address the issues associated with baseline and leakage estimates. In addition, soil monitoring is being conducted using laser-induced breakdown spectroscopy (LIBS), being developed by the Los Alamos National Laboratory.

Benefits

This project is very important because it is validating technology and developing protocols to measure carbon both in soils and in above ground vegetation. Although most of the sites being surveyed are in South America, the technology is easily transferable to other areas.

Examples of interpretation of sub-vegetation types within 1 ha "plots" in the Pine-Savanna Vegetation in the Rio Bravo Carbon Sequestration Pilot Project Using Digital Aerial Imagery to estimate the carbon stocks.



Designing a destructive sampling protocol for a heterogeneous landscape. Guaraqueçaba Climate Action Project, Paraná, Brazil.

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*Factsheet Under Development

Development of a Carbon Management Geographic Information System for the US*
-MIT

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***Factsheet Under Development**

Economic Evaluation of CO_2 Sequestration Technologies*
-Tennessee Valley Authority

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PROJECT facts

Sequestration

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

03/2003

MIDCONTINENT INTERACTIVE DIGITAL CARBON ATLAS AND RELATIONAL DATABASE (MIDCARB)

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Background

Current federal energy policy assumes that fossil fuels will continue to be the primary source of energy for the United States and the world well into the 21st century. However, there is growing concern about the possible role of increasing atmospheric concentration of carbon dioxide (CO_2) on climate change. For this reason, it may become necessary to manage anthropogenic CO_2 emissions. Sequestering CO_2 in geological reservoirs may be one way to safely store carbon over long periods of time, if the proper data and tools to analyze the geological feasibility as well as the associated costs can be developed.

The Midcontinent Interactive Digital Carbon Atlas and Relational DataBase (MIDCARB) is a joint project between the State Geological Surveys of Illinois, Indiana, Kansas, Kentucky, and Ohio, with funding from the Department of Energy's National Energy Technology Laboratory. The purpose of MIDCARB is to enable the evaluation of carbon sequestration potential in these sponsoring states. When completed, the digital spatial database will allow users to estimate the amount of CO_2 emitted by sources (such as power plants, refineries and other fossil fuel consuming industries) in relation to geologic reservoirs that can provide safe, secure sequestration sites over long periods. MIDCARB is organizing and enhancing the critical information about CO_2 sources and developing the technology needed to access, query, model, analyze, display, and distribute natural-resource data related to carbon management.

Large stationary sources of CO_2 emissions are identified, located, and characterized. Potential CO_2 sequestration sites, including producing and depleted oil and gas fields, unconventional oil and gas reservoirs, uneconomic coal seams, and saline aquifers, will be characterized to determine quality, size, and geologic integrity. All information will be available online through user query and will be provided through a single interface that will access multiple servers in each state. The approach is one of the first demonstrations of a large scale distributed natural resource databases and geological information. Access to the up-to-date technical information can be used at the regional and national level as a tool to minimize the negative economic impact and maximize the possible value of the CO_2 sequestration to hydrocarbon recovery from oil and gas fields, coal beds, and organic-rich shales.

Midcontinent Interactive Digital Carbon Atlas and Relational DataBase (MIDCARB)

PROJECT PARTNERS

University of Kansas Center for Research

The US Geological Survey

TOTAL ESTIMATED COST

Total Project Value	\$3,307,515
DOE	\$2,436,690
Non-DOE Share	\$ 870,825

Primary Project Goal

The goal of the proposed project is to improve the relational database management system with spatial query capabilities to evaluate the geographic distribution, physical characteristics, and economic parameters of potential CO_2 sources and geologic sequestration sites. Potential geologic sequestration sites include oil and gas fields, coal beds, unconventional oil and gas reservoirs, and saline aquifers.

Objectives

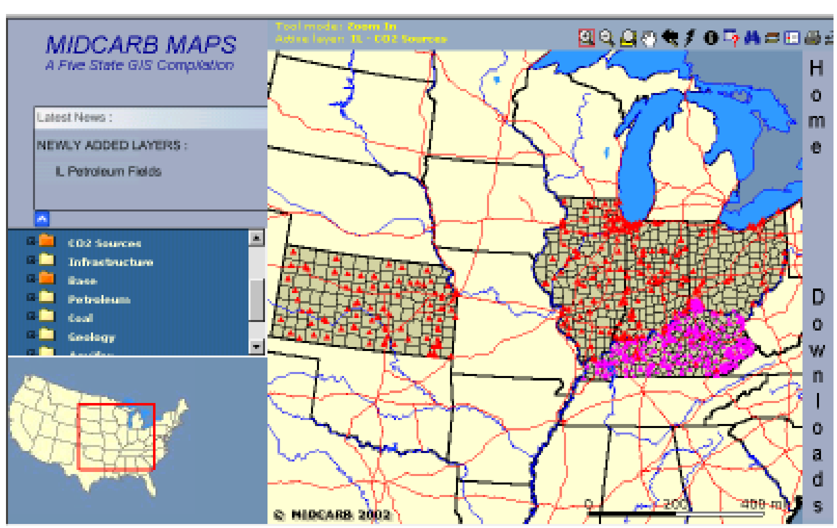
- Develop improved online tools to provide real-time display and analyze CO_2 sequestration data.
- Enhance the current webpage by making it more user friendly, design a more advanced query, and provide more options.
- Increase the server strength and efficiency.
- Add reservoir volumetric parameters and more and structural map information.

Accomplishments

MIDCARB map server is active and currently running on the internet. The MIDCARB interactive site can be utilized by accessing the following web address: *http://www.midcarb.org*

Benefits

The MIDCARB project will benefit the power industry by providing improved online tools for the real-time display and analysis of CO_2 sequestration data. The system links together data from sources, sinks and transportation within a spatial database that can be queried online. MIDCARB can assist decision makers by providing access to common sets of high quality data in a consistent manner.



Screen shot of the MIDCARB interactive map program.
Source: http://www.midcarb.org

Proj226.pmd

***Factsheet Under Development**

CO_2 Reservoir Improvements
-ANL

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PROJECT facts

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

04/2003

GEOLOGIC SEQUESTRATION OF CO_2 IN A DEPLETED OIL RESERVOIR: A COMPREHENSIVE MODELING AND SITE MONITORING PROJECT

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Background

Carbon dioxide (CO_2) injection into geologic formations is a promising strategy for the long-term sequestration of anthropogenic CO_2. This technique is likely to be needed to sustain the U.S.'s fossil fuel-based economy and to maintain our high standard of living. Subsurface injection of CO_2 into depleted oil reservoirs has the potential to be both cost effective and environmentally safe. However, CO_2 sequestration in oil reservoirs is a complex process spanning a wide range of scientific, technological, economic, safety, and regulatory issues. Detailed understanding of the many interactions is necessary before this option can become a safe and economic sequestration option, and its development requires a focused R&D effort by government and private industry.

Significant R&D gaps related to the sequestration of CO_2 in depleted oil reservoirs include the need to understand coupled physicochemical processes involving CO_2, water, oil, and reservoir rock; better estimates of the capacity of reservoirs for long-term sequestration; the ultimate fate of injected CO_2 (compared to short-term enhanced oil recovery); and improved remote (geophysical) monitoring technologies for accurately determining the dispersion of injected CO_2. Sandia National Laboratory and Los Alamos National Laboratory, along with New Mexico Tech, Colorado School of Mines and Kinder Morgan, have partnered with an independent producer, Strata Production Company, to investigate downhole injection of CO_2 into a depleted oil reservoir, the West Pearl Queen Field in New Mexico. This project is using a comprehensive suite of computer simulations, laboratory tests, and field measurements to understand, predict, and monitor the geochemical and hydrogeologic processes involved.

The following components are involved: geologic flow/reaction modeling; injection of CO_2 into a depleted oil-producing reservoir; geophysical monitoring of the advancing CO_2 plume; and laboratory experiments to measure reservoir changes due to CO_2 flooding. The models and data are being used to predict storage capacity and physical and chemical changes in reservoir properties, such as fluid composition, porosity, permeability, and phase relations. Science and technology gaps related to sequestration of CO_2 in depleted oil reservoirs will be identified as a result of this study.

Primary Project Goal

The overall objective of this project is to better understand, predict, and monitor CO_2 sequestration in a depleted sandstone oil reservoir. Injection into this reservoir was through an inactive well, while a producing well and two shutoff wells are being used for monitoring.

Geologic Sequestration of CO_2 in a Depleted Oil Reservoir: A Comprehensive Modeling and Site Monitoring Project

PARTNERS

Sandia National Laboratories

Los Alamos National Laboratory

New Mexico Tech University

Strata Production Company

Kinder-Morgan CO_2 Company

Colorado School of Mines

TOTAL ESTIMATED COST

Total Project Value	$4,830,000
DOE	$3,930,000
Non-DOE Share	$ 900,000

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Objectives

- Characterize the oil reservoir and its capacity to sequester CO_2 .
- Predict multiphase fluid migration and interactions.
- Deploy and evaluate improved remote geophysical monitoring techniques.
- Measure CO_2/reservoir reactions.
- Conduct computer simulations and lab measurements of fluid flow .
- Assess and predict complex geologic sequestration processes.
- Inject several thousand tons of CO_2 into a depleted oil reservoir .
- Establish pre-injection baseline and assess post-injection reservoir conditions to validate model predictions.

Accomplishments

Current geologic and preliminary flow simulation results indicated the feasibility of CO_2 injection into a depleted oil reservoir. Simulations have predicted plume travel times and suggest that the combined saturation and pressure difference waves generated by injected CO_2 can be monitored through use of seismic surveys. Simulations also provide guidelines for geophysical monitoring (e.g., spacing of sources and receivers). Geochemical experiments with Queen Sandstones have been initiated to understand the potential for in situ mineralization. These experiments show that carbonate cements dissolve over time.

Approximately 2,100 tonnes of CO_2, equivalent to one day's emissions from an average coal-fired power plant, have been injected into the formation. An extensive three-dimensional geophysical survey was conducted prior to CO_2 injection to provide the best possible subsurface image of the reservoir. As the CO_2 entered the reservoir at a rate of about 40 tons/day and a pressure of 1,400 psi, scientists used highly sensitive equipment to acquire microseismic signals to help track the movement of the plume. After the CO_2 has been allowed to "soak" into the reservoir rock, a second 3-D seismic survey will be taken. These observations will begin to tell scientists the fate of the CO_2 plume and will be used to calibrate, modify, and validate modeling and simulation tools.

Benefits

This project takes advantage of unique test opportunities for a pilot scale field experiment in a pressure-depleted oil reservoir to predict and monitor the migration and ultimate fate of injected CO_2. The models and data developed will be used to predict storage capacity and physical and chemical changes in reservoir properties, such as fluid composition, porosity, permeability, and phase relations. Science and technology gaps related to engineering aspects of CO_2 sequestration will be identified in this study. In addition, a better understanding of CO_2/reservoir interactions will improve enhanced oil recovery (EOR) flooding practices.

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*Factsheet Under Development

Ecosystem Dynamics and Economic Analysis*
-LANL

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PROJECT

facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

08/2002

DEVELOPMENT OF COMPREHENSIVE MONITORING TECHNIQUES TO VERIFY THE INTEGRITY OF GEOLOGICALLY SEQUESTERED CARBON DIOXIDE

PRIMARY PARTNERS

National Energy Technology Laboratory
Brookhaven National Laboratory
Los Alamos National Laboratory
Sandia National Laboratory
West Virginia University
OPHIR Corp.
Strata Production Company
Pecos Petroleum

DOE FUNDING PROFILE

Prior FY's	$319,000
FY2002	$400,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$ 719,000

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Background

One of the most critical research areas is aimed at monitoring the long-term storage stability and integrity of CO_2 in geologic formations. Research aimed at monitoring the integrity of CO_2 sequestered in geologic formations is certainly one of the most pressing areas of need if geologic sequestration is to become a significant factor in meeting this country's stated objectives to reduce greenhouse gas emissions. The most promising geologic formations currently under consideration for CO_2 sequestration are active and depleted oil and gas formations, brine formations, and deep, unmineable coal seams. Unfortunately, the long-term CO_2 storage capabilities of these formations are not well explored.

Primary Project Goal

The goal of this effort is to develop and demonstrate advanced monitoring techniques to assess the capacity, stability, rate of leakage, and permanence of CO_2 storage in geologic formations.

Objectives

- The primary objective is to evaluate a wide range of surface and near surface monitoring techniques that show promise in the detection of both the short term, rapid loss, and long-term, intermittent slow leakage of carbon dioxide from geologic formations.

- Monitor for carbon dioxide leakage at the West Pearl Queen Oil Field to ultimately determine the migration and fate of CO_2 after being injected into a depleted oil reservoir. Models and data developed will be used to predict physical and chemical changes in oil reservoir properties and the long-term storage capacity, safety, and integrity of oil reservoir sequestration.

- Monitor for carbon dioxide leakage at CO_2-ECBM/sequestration sites by conducting background studies of geophysical features, soil and atmosphere hydrocarbon patterns and concentrations, and monitoring locations and grid patterns for soil-gas sampling.

- Monitor with perfluorocarbon tracer compounds and evaluate tracer retention on coal.

- Perform geophysical site analysis from remote sensing and ground based measurements by combining satellite visible and infrared views with satellite radar and optical aerial photography.

Development of Comprehensive Monitoring Techniques to Verify the Integrity of Geologically Sequestered Carbon Dioxide

CONTACT POINTS

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Accomplishments

In previous years, work was completed on site selection for the initial field monitoring study. Agreements were made with various research agencies and state and federal environmental agencies to implement a monitoring program at the West Pearl Queen oil field site in southeast New Mexico where a carbon dioxide injection experiment will be conducted. An assessment of geological features at the New Mexico injection site was made from satellite images to aid in the placement of the chemical and optical monitors. Additionally, a contract was obtained for the services of the OPHIR Corp. to conduct a background survey of the atmospheric concentrations of CH_4, C_2H_6, and C_3H_8 at the injection well site, and surrounding area.

A group of novel tracer compounds was selected and the analytical protocol for their detection and quantification was decided upon.

A monitoring protocol was developed to maximize tracer detection. Techniques have been developed to sample soil gases for the tracers using an active gas sam-pling technique. A sampling pump was designed and several sampling systems were constructed at NETL. The protocol was evaluated at NETL prior to field-testing.

Benefits

Development of techniques to monitor the integrity of geologically sequestered CO_2 is needed to assure public health and safety and to gain public acceptance of geologic sequestration technology. Active and depleted oil and gas formations, brine formations, and deep coal seams that were previously unused now have the potential to serve as sinks for carbon dioxide sequestration. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that may further increase global warming.

Spectroscopic Measurements – OPHIR Corp.
West Pearl Queen Field, New Mexico

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*Factsheets Under Development

Development of simulation tools for sequestration and retention of CO_2 in permeable media*
-NETL

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Breakthrough Concepts

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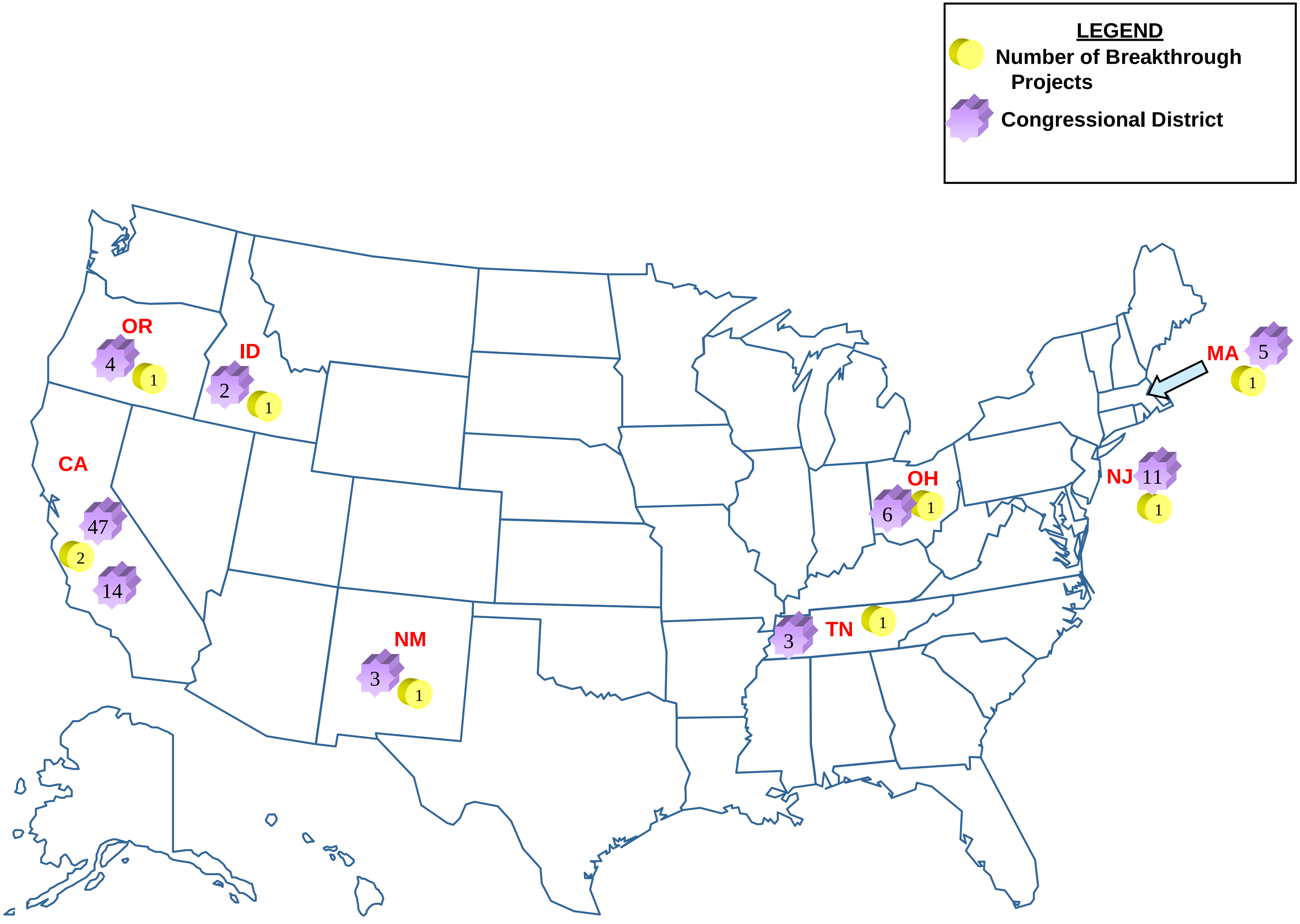

Doesn't include NETL Projects

Breakthrough Concepts Congressional Districts List

Project Title	Primary Contractor	Congressional District
Recovery & Sequestration of CO_2 from Stationary Comb. Systems by Photosynthesis of Microalgae	Physical Sciences, Inc.	MN05
Chemical Fixation of CO_2 in Coal Combustion Products and Recycling Through Algal Biosystems	Tennessee Valley Authority	TN03
Enhanced Practical Photosynthetic CO_2 Mitigation	Ohio University	OH06
Fuel-Flexible Gasification-Combustion Technology for Production of H_2 and Sequestration-Ready	GE Energy and Environmental Research Corporation	CA47
CO_2 Mineralization	Albany Research Center	OR04
Photoreductive Sequestration of CO_2 to Form C1 Products and Fuel	SRI International Corporation	CA14
Advanced CO_2 Cycle Power Generation	Foster Wheeler	NJ11
Enhancement of CO_2 Emissions Conversion Efficiency by Structured Microorganisms (cyano-bacteria conversion of CO_2)	INEEL	ID02
Mineral Sequestration of CO_2 - Chemical Dissolution Approaches	LANL	NM03

Breakthrough Concepts

Technology Target:

- Biogeochemical - Discover new biological and chemical CO_2 conversion processes
- Mineralization - Identify large-scale marketable uses
- Power Design Concepts - Produce near-zero emission process

Biogeochemical
- Photobioreactor for algae cultures

PSI/Hawaii ($1.68M)(00-03)
- CO_2 photosynthesis of microalgae
- Selection of microalgae
- Demonstrate industrial scale photobioreactors
- Economic analysis

Ohio Univ. ($1.08M)(00-03)
- Practical photosynthetic conversion of CO_2
- Demonstrate and optimize lower-risk methods of CO_2 mitigation based on existing biological organisms

TVA ($0.6M)(00-03)
- CO_2 recycling through algal biosystems

SRI ($0.10M)(02-03)
- Photoreductive Seq of CO_2
- Demonstrate if C1 products and fuel can be efficiently made by enhanced sunlight and semiconductor methods

INEEL ($0.33M)(99-02)
- Cyano-bacteria conversion of CO_2 to hydrocarbon product

Project Funding: DOE $3.8M / Shared $1.1M

Mineralization
- Continuos mineral carbonation reactor POC

Albany Research Center ($1.2M)(01-03)
- React calcium and/or magnesium silicate with CO_2

LANL ($2.1M)(98-03)
- Mineral carbonation chemistry
- Explore, technical, economic, and environmental issues

Project Funding: DOE $3.3M / Shared $0.3M

Power Design Concepts
- Fuel-flexible advanced gasification-combustion concepts

GE-GEERC - $2.5M)(00-03)
- Advanced power cycle with CO_2 concentration

Foster Wheeler - $0.24M (02-04)
- Conceptual design to separate CO_2 without compressor

Project Funding: DOE $2.7M / Shared $0.94M

NETL

Breakthrough Concepts Project Fact Sheet List

Project Title	Primary Contractor	Fact Sheet Listing
Recovery & Sequestration of CO_2 from Stationary Comb. Systems by Photosynthesis of Microalgae*	Physical Sciences, Inc.	B-5
Chemical Fixation of CO_2 in Coal Combustion Products and Recycling Through Algal Biosystems*	Tennessee Valley Authority	B-7
Enhanced Practical Photosynthetic CO_2 Mitigation*	Ohio University	B-9
Fuel-Flexible Gasification-Combustion Technology for Production of H_2 and Sequestration-Ready*	GE Energy and Environmental Research Corporation	B-11
CO_2 Mineralization*	Albany Research Center	B-13
Photoreductive Sequestration of CO_2 to Form C1 Products and Fuel*	SRI International Corporation	B-15
Advanced CO_2 Cycle Power Generation*	Foster Wheeler	B-17
Enhancement of CO_2 Emissions Conversion Efficiency by Structured Microorganisms (cyano-bacteria conversion of CO_2)*	INEEL	B-19
Mineral Sequestration of CO_2 - Chemical Dissolution Approaches*	LANL	B-21

* Factsheet Under Development

*Factsheet Under Development

Recovery & Sequestration of CO_2 from Stationary Comb. Systems by Photosynthesis of Microalgae*
-Physical Sciences, Inc.

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*Factsheet Under Development

Chemical Fixation of CO_2 in Coal Combustion Products and Recycling Through Algal Biosystems*
-Tennessee Valley Authority

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*Factsheet Under Development

Enhanced Practical Photosynthetic CO_2 Mitigation*
-Ohio University

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***Factsheet Under Development**

Fuel-Flexible Gasification-Combustion Technology for Production of H_2 and Sequestration-Ready*
-GE Energy and Environmental Research Corporation

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*Factsheet Under Development

CO_2 Mineralization*
-Albany Research Center

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*Factsheet Under Development

Photoreductive Sequestration of CO_2 to Form C1 Products and Fuels*
-SRI International Corporation

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*Factsheet Under Development

Advanced CO_2 Cycle Power Generation*
-Foster Wheeler

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*Factsheet Under Development

Enhancement of CO_2 Emissions Conversion Efficiency by Structured Microorganisms (Cyano-bacteria conversion of CO_2)*
-INEEL

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*Factsheet Under Development

Mineral Sequestration of CO_2 - Chemical Dissolution Approaches*
-LANL

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Non-CO_2 GHG Mitigation

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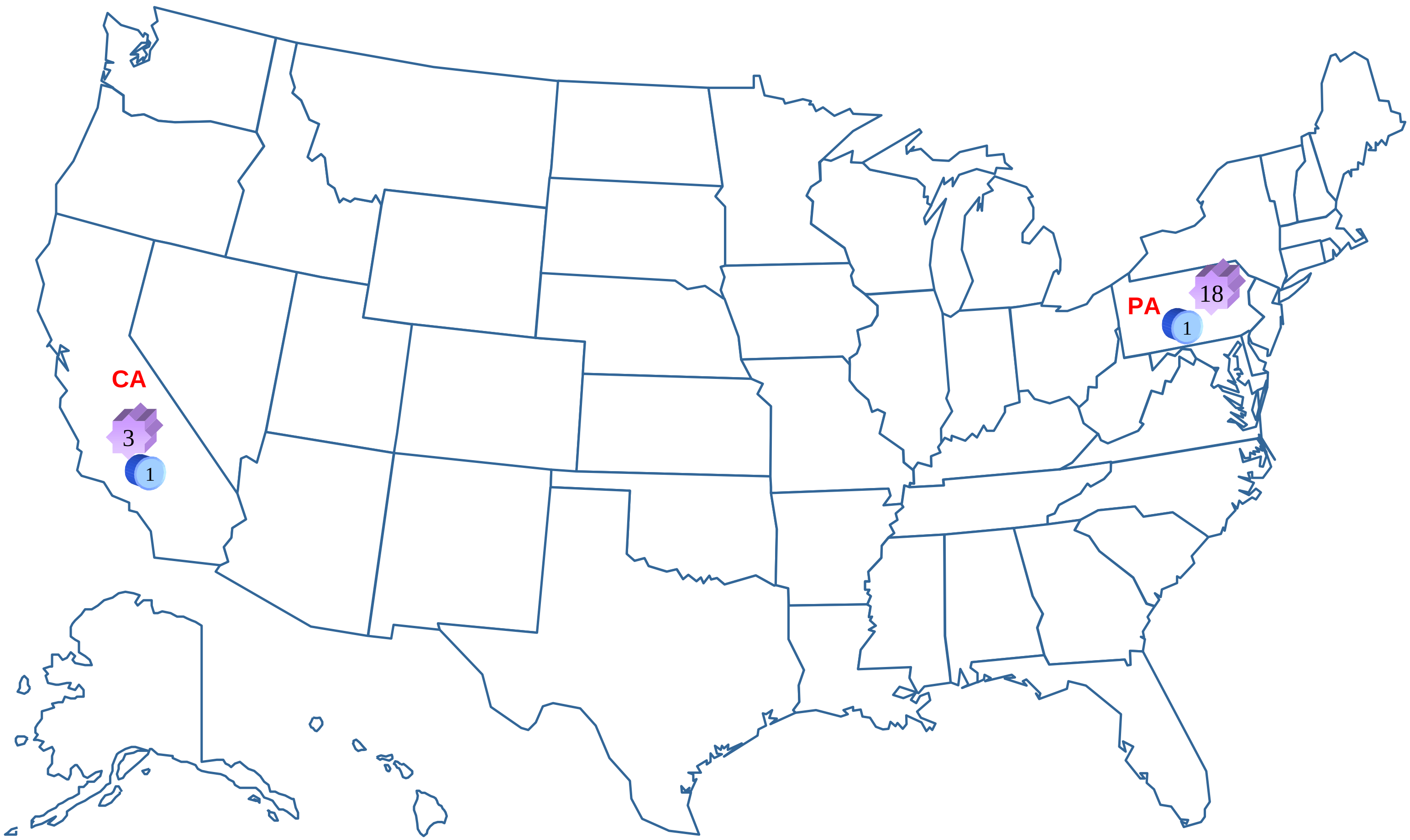
Non CO_2 GHG Mitigation Projects

LEGEND

Number of Non CO_2 GHG Projects

Congressional District



*Doesn't include NETL Projects

3/27/03

Project Title	Primary Contractor	Congressional District
Full-Scale Bioreactor Landfill	Yolo County	CA03
Capture and Use of Coal Mine Ventilation Air Methane	CONSOL Energy Inc.	PA18

Non-CO_2 GHG Mitigation

Technology Target

- Demonstration viability of large-scale oxidation of coal mine ventilation air methane
- Technology options for land fill gas

DOE $2.18M / Shared $1.59M

Yolo - $0.56M (01-04)
- Full-scale Bioreactor Landfill for abating GHG related to organic wastes
- Data collection & monitoring og landfill methane gas with bioreactors

CONSOL - $1.62M (02-04)
- Use of coal mine ventilation air methane
- Demonstration flow reversal of ventilation air methane

NETL

Project Title	Primary Contractor	Fact Sheet Listing
Full-Scale Bioreactor Landfill	Yolo County	N-5
Capture and Use of Coal Mine Ventilation Air Methane*	CONSOL Energy Inc.	N-7

* Factsheet Under Development

PROJECT facts

Sequestration

10/2002

U.S. Department of Energy
National Energy Technology Laboratory

Full-Scale Bioreactor Landfill

Background

Sanitary landfilling is the dominant method of solid waste disposal in the United States, accounting for about 217 million tons of waste annually (U.S. EPA, 1997). The annual production of municipal waste in the United States has more than doubled since 1960. In spite of increasing rates of reuse and recycling, population and economic growth will continue to render landfilling as an important and necessary component of solid waste management.

As a part of the Environmental Protection Agency's (EPA) Project XL program to develop innovative approaches while providing superior greenhouse gas emissions protection, the Yolo County Department of Planning and Public Works is constructing a full-scale bioreactor landfill. In a bioreactor landfill, controlled quantities of liquid (leachate, groundwater, grey-water, etc) are added to increase the moisture content of the waste. Leachate is then recirculated as necessary to maintain the moisture of the waste at or near its moisture holding capacity. This process significantly increases the biodegradation rate of waste and thus decreases the waste stabilization and composting time (5 to 10 years) relative to what would occur within a conventional landfill (30 to 50 years or more). If the waste decomposes in the absence of oxygen (anaerobically), it produces landfill gas, primarily a mixture of methane, a greenhouse gas. Methane is 21 times more potent than CO_2 in its effects on the atmosphere. This by-product of anaerobic landfill waste composting can be a substantial renewable energy resource that can be recovered for electricity or other uses.

In the initial phase of this project, a 12-acre module divided into several cells was constructed. The cells are highly instrumented to monitor bioreactor performance. The final phase pertaining to carbon sequestration involves evaluating full-scale performance and potential of aerobic and anaerobic bioreactor landfill cells as tools for abating greenhouse gas (GHG) emissions related to organic wastes in landfills.

Primary Project Goal

The goals of this project are to construct, then evaluate full-scale performance and potential of aerobic and anaerobic bioreactor landfill cells as tools for abating greenhouse gas emissions related to organic wastes in landfills. The greenhouse gas (GHG) abatement is accomplished by routes including sequestration of photosynthetically derived carbon in wastes, CO_2 offsets from energy use of waste-derived gas, and mitigation of methane emission from the wastes.

PRIMARY PARTNER

Yolo County

Solid Waste Association of North America

Institute for Environmental Management

TOTAL ESTIMATED COST

Total	$1,748,103
DOE	$ 563,000
Non-DOE	$1,185,103

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

NETL

Full-Scale Bioreactor Landfill

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Objectives

- Evaluate full-scale performance and potential of aerobic and anaerobic bioreactor landfill cells as tools for abating GHG emissions related to organic wastes in landfills.
- Operate and measure the performance of anaerobic an bioreactor module to desired endpoint
- Conduct analysis and interpretation of the data.

Accomplishments

In the initial phase of this project, the landfill cells have been constructed and filled with waste. Instrumentation, monitoring, and gas collection systems are in place and used to measure and independently record data from each other. The data from these sensors is automatically recorded and sent to the Yolo County office. The County will construct the second phase of module D over the next two years and, depending on the results of the first phase, Yolo County may operate the next phase either anaerobically or aerobically.

Benefits

This process will significantly increase the biodegradation rate of waste and thus reduce the waste stabilization and composting time by 67-80% and provide a substantially improved renewable energy resource that can be recovered for electricity or other uses. This means that the energy market could increasingly depend on this type of renewable energy for the provision of electric generation. Another benefit of the bioreactor landfill is that it generally improves the gas generation rate, decreasing the time frame of landfill gas generation from several decades to between 5 to 10 years.

A covered bioreactor landfill

Filling a bioreactor landfill

*Factsheet Under Development

Capture and Use of Coal Mine Ventilation Air Methane*
-CONSOL Energy Inc.

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Carbon Sequestration Participants Index

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Texas Engineering Experiment. Station	OV-6, S-2, S-4, S-6, **S-22**
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Universidad Austral de Chile	**M-12**
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University of California at St. Louis Obispo	
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